



from



Version 3.0

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Welcome to Virtual Grower 3.0

Thank you for your interest in Virtual Grower. Since we released Virtual Grower 1.0 in early 2006, we have attempted to work with representatives from the greenhouse industry to improve the software's capabilities. This version represents some of the largest, most comprehensive changes in the software between releases to date. We believe you will still find the ease-of-use and simplicity of navigation from the original software. This new version now has an additional 600 U.S. sites so you will be more likely to find a good, representative weather database to match your needs. The entire interface has been redesigned as well in order to meet new computer requirements or needs; Virtual Grower 3.0 is now Mac and PC compatible, and can now run on newer 64-bit processors. We recognize that not all these changes will be identified from any single user, but the changes are significant because more people can now make use of the software.

Users familiar with older version will still find features like predicting plant growth and development for selected species, improved descriptions of air infiltration into your simulated greenhouse, and additional energy curtain options. The software still allows for simulations of supplemental lighting features and we have improved the calculations for energy curtains. If you have a connection to the internet while you are running the software, you can take obtain two-day forecasts of weather and simulate the short-term heating and lighting needs during these times. Finally, the output section was enhanced to provide more visual feedback options – graphs and figures – for the cost of running our facilities.

The vast majority of features that have been added to Virtual Grower over the years were based on suggestions from users. As always, we want to hear from you. If you have a problem, complaint, or suggestion, please send us an email at USDA-ARS@utoledo.edu and we will respond to you inquiry as soon as possible.

Setup Requirements

Virtual Grower 3 is compatible with computers running Windows XP, Vista, Windows 7, and Mac OSX 10.4.11 (a.k.a. Leopard) and above. A working copy of the Java Virtual Machine (JVM) version 5 or above must be installed on the system. You can download the JVM from <http://java.com/> or install from the executable from the CD.

Installation

Virtual Grower 3 does not require a system installation. If you have a CD, simply copy the files from the CD to the desired folder on your system and run the "Virtual_Grower_3.jar" file to launch Virtual Grower 3. Alternatively, you can double click on the VG3 icon (3 orange gerbera daisy flower cluster) to launch the program. If you downloaded Virtual Grower 3, double click on the executable file called "Virtual Grower 3 – PC" (for PC computers) or "Virtual Grower 3 – Mac" (for Mac). This action extracts the folder called "Virtual Grower 3" to the same location that Virtual Grower 3 – PC/Mac was located. After extraction simply

navigate to the location of the files and double click on “Virtual Grower 3.jar” or the Virtual Grower 3 icon to launch the program.

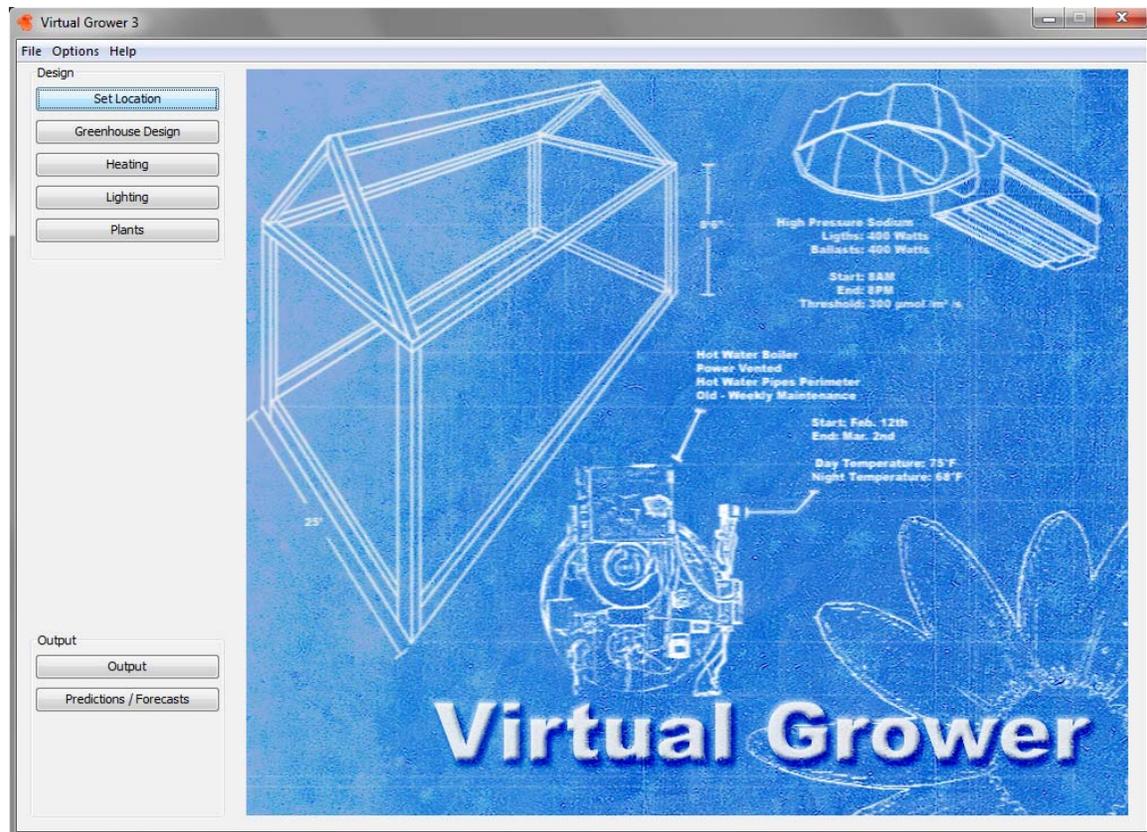
Uninstalling and Repairing

Since Virtual Grower 3 is not installed on the system, you only need delete the Virtual Grower 3 files to remove it from your system. To repair missing or corrupt Virtual Grower 3 files, simply copy the files from the CD over the existing files or extracted the downloaded file to the existing directory. When prompted by the system to overwrite or skip, choose the overwrite option.

If you have downloaded the software and have difficulty running it, please contact USDA-ARS@utoledo.edu and we will gladly work with you to ensure you can use the software.

Getting Started

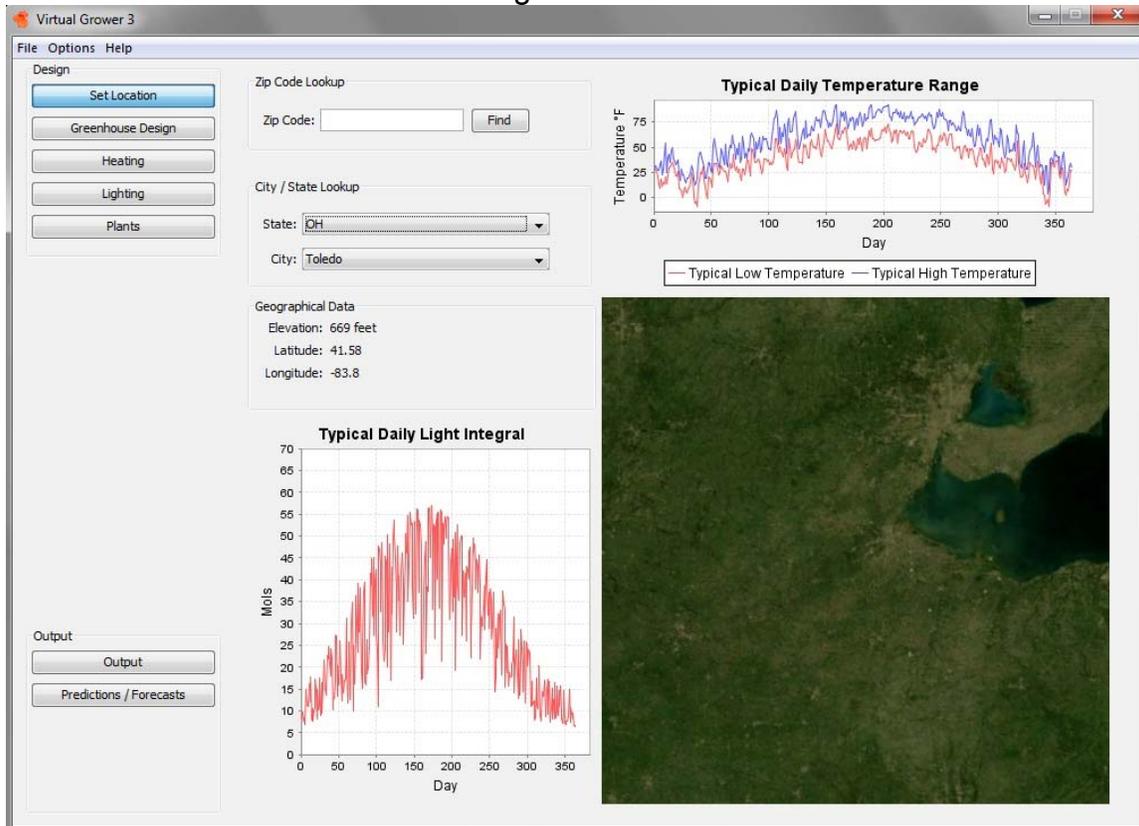
Once the Virtual Grower 3 folder is copied onto your hard drive or desktop, open the folder and double click on the “Virtual Grower 3.jar” file to launch the program. The Main Page should appear:



Along the left side of the page, there are buttons “Set Location,” “Greenhouse Design,” “Heating,” “Lighting,” “Plants,” “Output,” and “Predictions/Forecasts.” By clicking on those buttons, those sections will appear. The manual will describe each section beginning at the top.

Set Location

The first step in building a greenhouse within the software is to choose a location. This is done within the Set Location area. Clicking on the “Set Location” button reveals the following screen:



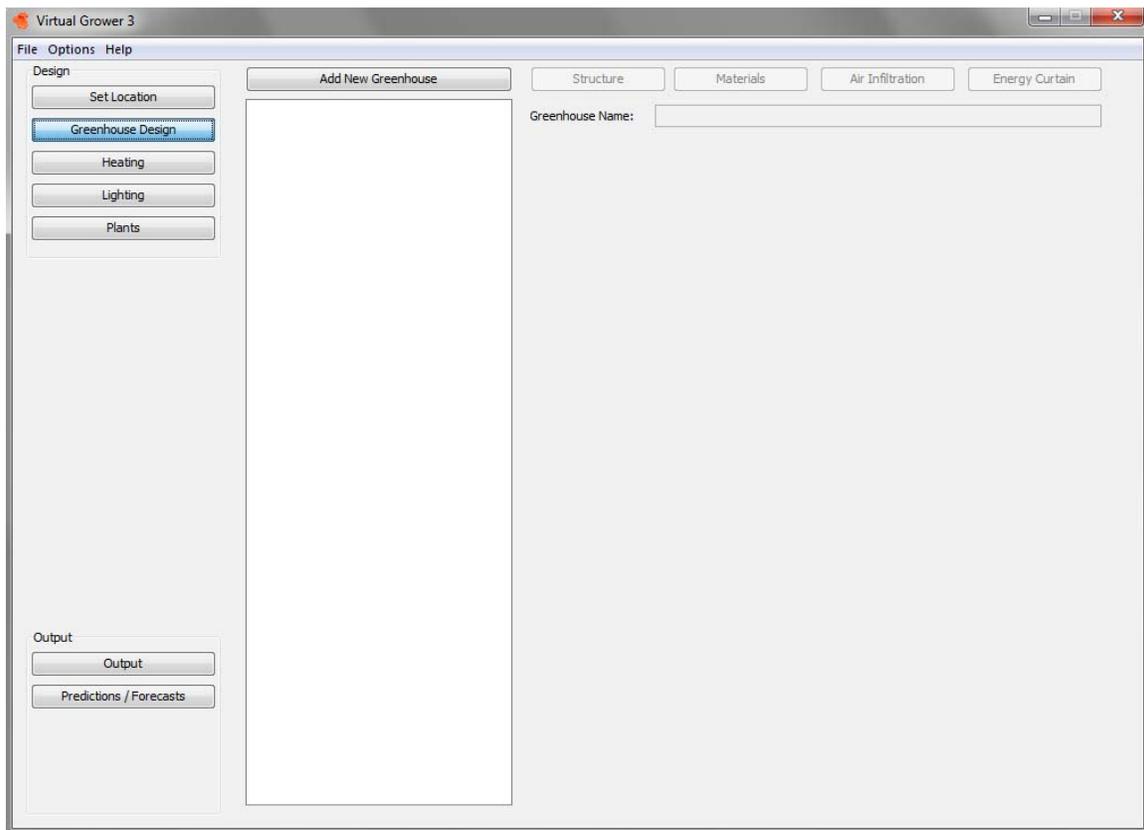
To select your location, either enter your postal zip code (first 5 digits only) and click the “Find” button, or select your state and city from the drop-down menus within the City/State Lookup area. The default settings are Toledo, Ohio. There are now 785 sites within the U.S. that are included in the software, but still not all cities within a state are represented. Choose one that is closest to you if your city is not represented. For example, in the state of Ohio, a user in Bowling Green would choose the city of Toledo since Bowling Green is not currently in our database. [Still can't find a city that's close to yours? Contact us at USDA-ARS@utoledo.edu and we will work with you to try and find one that best suits your needs.]

Selecting your location loads an historical database of weather information. This gives typical values of temperature, light, and cloud cover, for example, for each hour over the course of 12 months. Data for temperature and daily light integral is displayed for the selected location in graphs at the top right and bottom, middle of this picture. Selecting new locations will immediately update these graphs, and in this way, it is possible to roughly compare different sites. This weather information was obtained from the National Renewable Energy Laboratory website (<http://rredc.nrel.gov/>). It is important to note that the

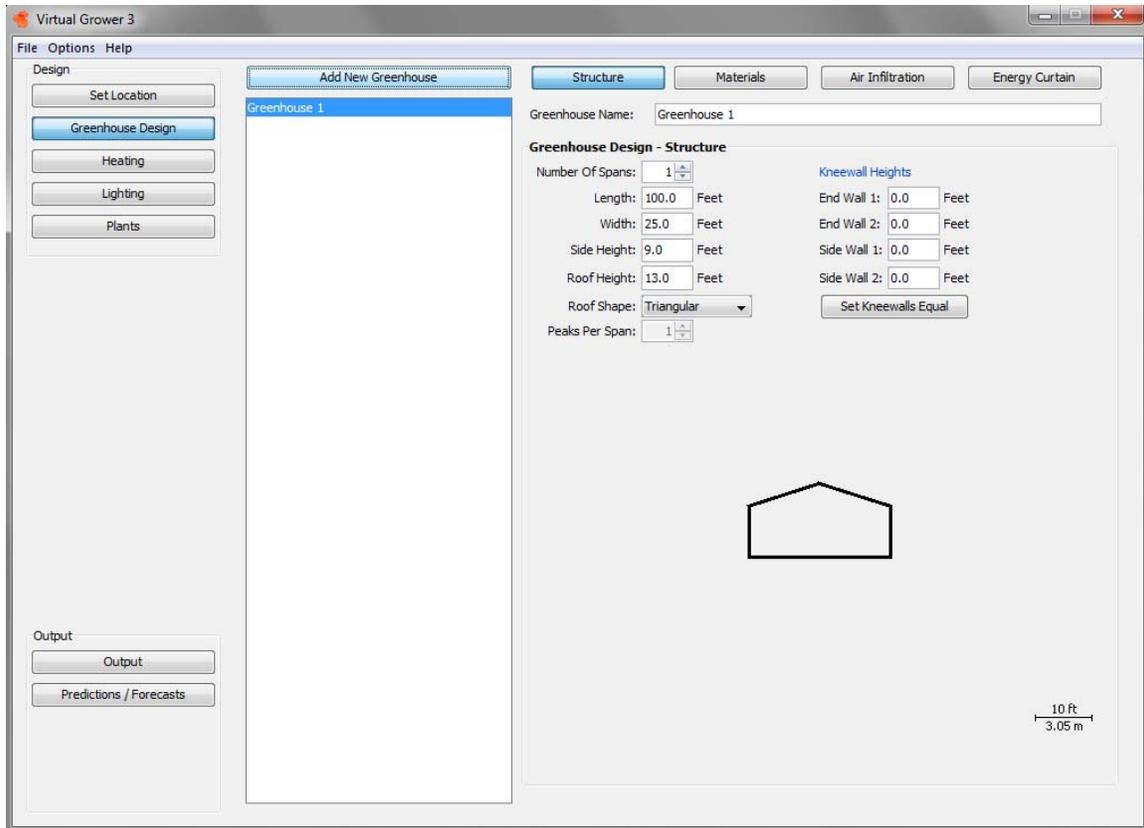
weather information is not average values for a period of time, but typical or representative values for that date and time. Finally, the large map in the lower right corner centers on your selected location, which serves as a reference point to ensure your location was properly selected.

Greenhouse Design

This is the section that will allow you to design and describe the physical characteristics of your greenhouse: the structure, the materials, construction quality and energy curtain systems. After clicking on the Greenhouse Design button to the left side of the screen, the following screen should appear:

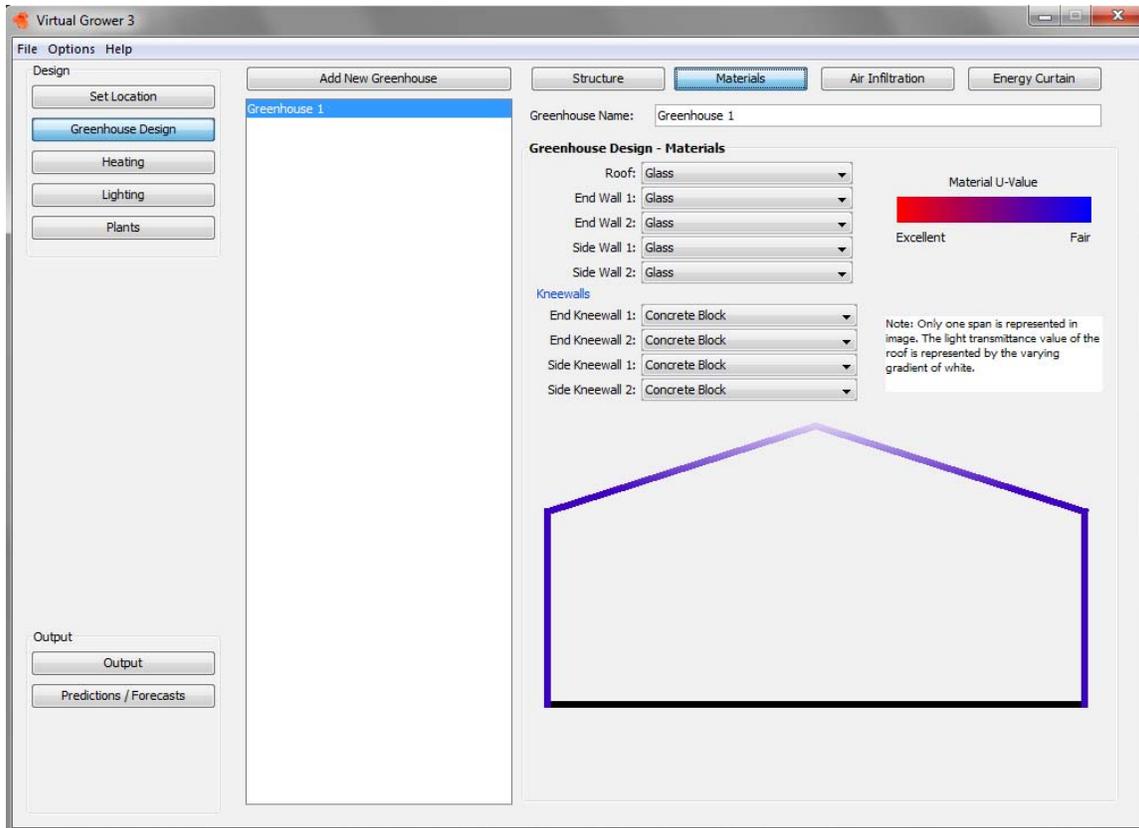


Across the top of the screen, there are five buttons: “Add New Greenhouse,” “Structure,” “Materials,” “Air Infiltration,” and “Energy Curtain.” All but the first are initially inactivated (light grey text) in the default view. Your only option is to click on the “Add New Greenhouse” button. The following screen then appears:



A default, basic greenhouse is constructed that, in cross section, looks like the picture on the right side of the screen. The name of the greenhouse is initially highlighted in blue, but can be changed on the right half of the screen, near the top, in the space next to “Greenhouse Name:”. General construction description can be completed here including number of spans, length, width, heights and side and peak, roof shape, and kneewalls. As changes are made in this section, the diagram will automatically change to reflect the new design. Note the scale in the lower right corner of the image area – this will update itself on larger or smaller diagrams. Quonset style houses can be constructed by changing the side height to 0.

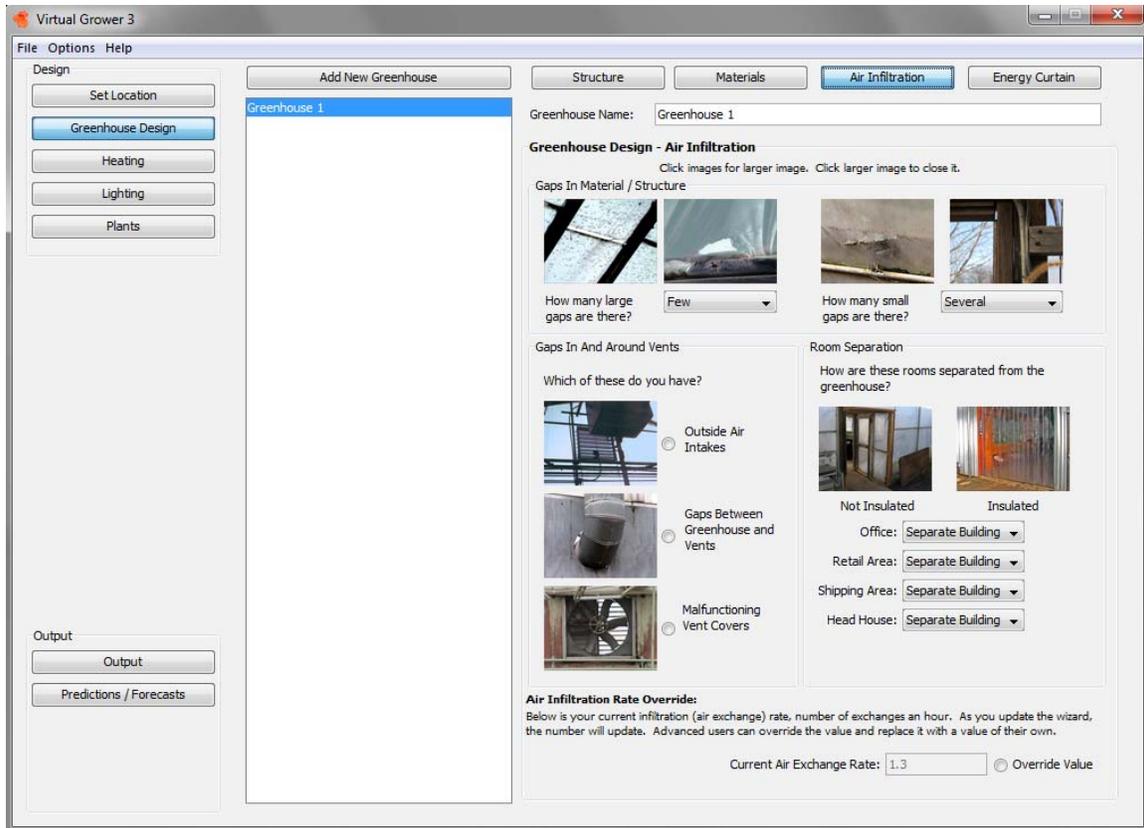
Commercial greenhouses often evolve over long periods of time and the result can be unique combinations of greenhouse structures and materials. This is neither “right” or “wrong” because it works for you. To better define those unique combinations of materials and designs, click on the “Materials” button. The following screen should appear:



On this screen, a user can select different materials from the drop-down menus next to each greenhouse side or kneewall section. There is an image of one representative greenhouse section in the lower half of the right side of the screen. The color represents insulative value (U-value), with red indicating highly resistant to heat loss and purple indicating less resistance to heat loss. An additional layer of information is in the varying shade of white on the roof; this represents the extent of light transmission through the material with more white indicating more light transmittance. As selections in materials are made, the colors on the diagram will change. Note that if no kneewalls are built in the "Structure" section, no color changes will result from changing the kneewall materials.

Air Infiltration

An important part of describing a greenhouse is getting a reasonable estimate of how tightly sealed it is. That is, a greenhouse with high infiltration (a lot of leaks) is more difficult to control for growth environment. Clicking on the Air Infiltration button should reveal the following screen:

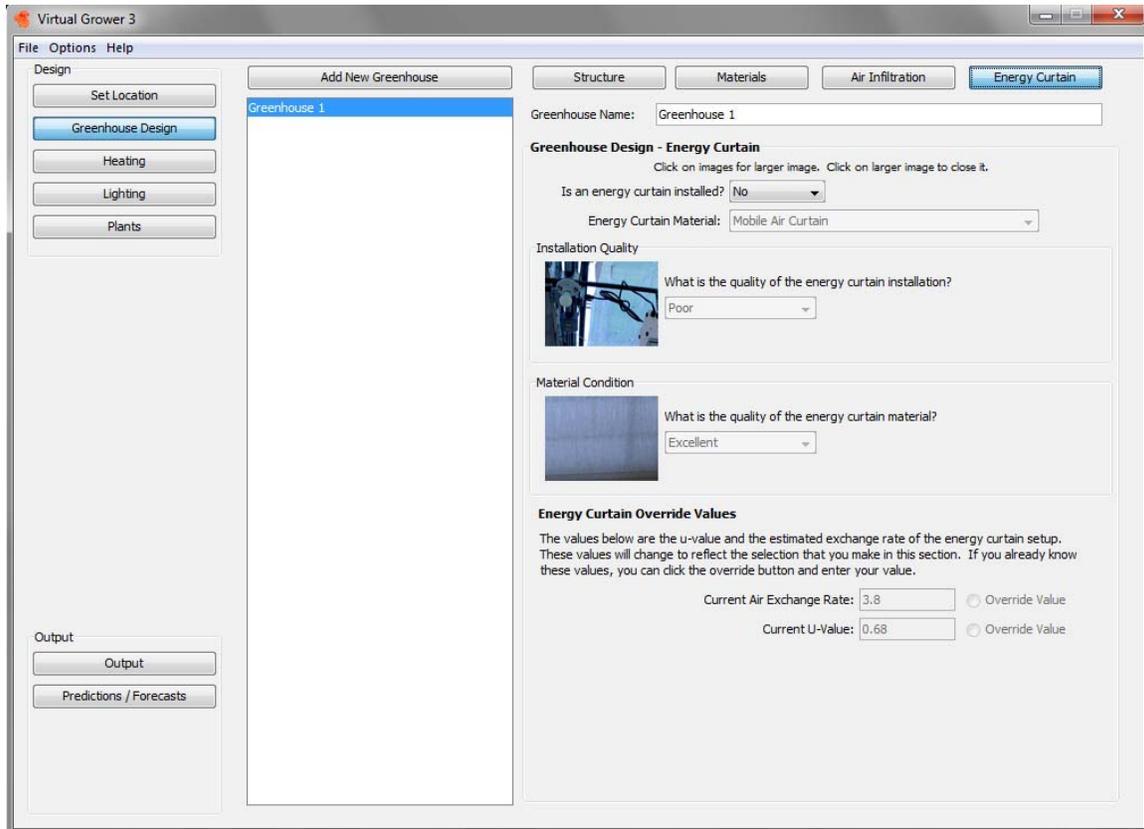


This page has several pictures of commonly encountered sources of air infiltration in many greenhouses along with a few terms to describe how frequently these sources of air infiltration would be encountered in your greenhouse. Clicking on the pictures once will enlarge the image for closer inspection, and clicking the enlarged image will reduce it again. As selections from the drop-down menus for descriptions of frequency are made, an air exchange rate is estimated. Air exchange rates are quantified as number of volumes of air equivalent to the inside of your greenhouse gets exchanged with outside air (or another air source) per hour. As a reference, a newly constructed greenhouse that is well insulated and has no gaps present has an air exchange rate likely around 0.5. An older greenhouse with many gaps, cracks in panels or doors, and malfunctioning vent covers can have an air exchange rate of well over 5.

Describing the gaps in materials, around vents and vent covers, and between rooms will result in changes to the air exchange rate that appears in the lower right corner of this screen. This is a tool only and should be used for estimating purposes only – it is not a substitute for a thorough energy audit performed by a professional greenhouse engineer. If you have information as to what your air exchange rate might be or if you want to try different values for simulation purposes, click the “Override Value” button and type in a number from 0 to 100 in the blank space.

Energy curtains

The final area for describing the physical appearance and function of your greenhouse is in the “Energy Curtain” button. As the name implies, the section helps describe the general energy curtain system in much the same way as the Air Infiltration section describes leakage. Clicking on that button should reveal the following screen:

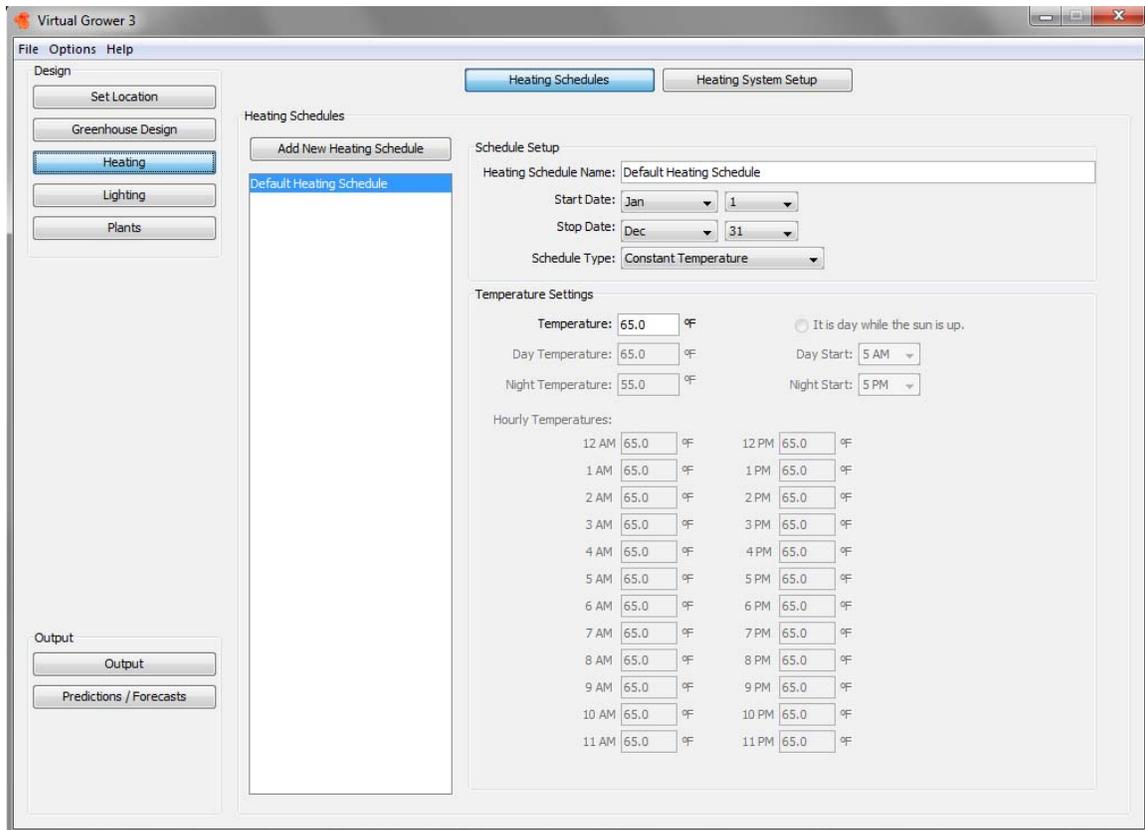


If no energy curtain is installed in your greenhouse, there is no need to change the default settings. If you would like to include an energy curtain in your simulation, choose “Yes” from the drop-down selection after the question “Is an energy curtain installed” on the right side of the screen near the top. This will activate the questions and values below this initial question to allow for further description. Again, there are pictures on this screen, which can be enlarged by clicking on an image. Clicking on the enlarged image again will close that image. There are three areas that must be addressed for this section to derive an estimate of the insulative value of the energy curtain: 1) the user is required to select what energy curtain material is being used from the drop-down list of options, 2) The next area asks about the installation quality, and 3) the final area asks about the energy curtain’s material condition. Selections made in these areas will help define an estimate for the air-exchange rate between the above-curtain and below-curtain zones as well as a U-value of the curtain structure. This is an estimate only – if a thorough energy audit is performed on your installation, the override buttons can be selected allowing you to enter other

values for air exchange rate and U-value. For further information on how energy flux is impacted with an energy curtain, see Appendix 2.

Heating

The next area allows a user to define their heating system, heating schedules, and fuel type with unit costs. Clicking on the “Heating” button on the left side of the screen should result in the following screen:



Heating Schedules

In this section, heating schedules can be defined. Since different greenhouse zones or structures can have unique heating systems and schedules, this area allows a user to define many different schedules that can later be matched to specific greenhouses or apply a single heating schedule to multiple greenhouses. To the left side of the screen, a large white field with a blue bar can be populated with additional heating schedule names. The blue highlight is the selected schedule that can be renamed or altered with the information on the right side of the screen. Just above the name field, there is an “Add New Heating Schedule” button. A new, default schedule will be created with each click of this button. To begin, you can change the schedule name (default name is “Default”). Select the start and stop dates by selecting month and day. Then select the schedule type from the drop-down menu, which

includes “Constant Temperature,” “No Heating,” “Day and Night Temperatures,” and “Hourly Temperatures”.

Constant Temperature The temperature is the same, day and night, during the dates that are defined below in the temperature settings area.

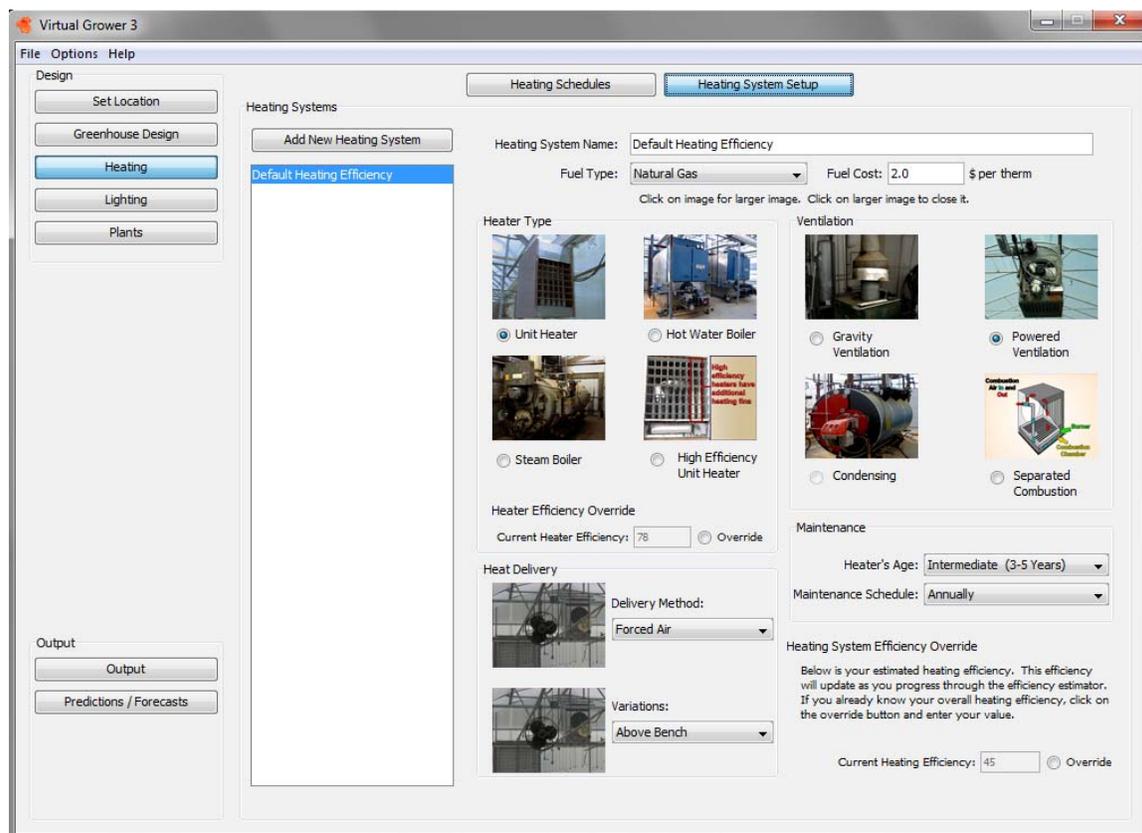
No Heating Greenhouse is not heated so no cost is calculated for that house.

Day and Night Temperatures The daytime and nighttime temperature setpoints are defined in the “Temperature Settings” area below. If you desire for the day and night to reflect the natural day and night length (that is, the length of each change throughout the year but is based on location), activate the button “It is day while the sun is up.” If a consistent thermoperiod is desired independent of the natural sunrise and sunset, times for when the day and night start can be selected in the temperature settings section.

Hourly Temperatures Temperatures can be defined for each hour of the day, which enables the user to define DIF or DIP treatments that require brief, significant changes in temperature at specific times in the day.

Heating System Setup

In the “Heating System Setup” area, users can define different heating systems, fuels, fuel costs, and efficiencies. Clicking on the “Heating System Setup” button at the top within the Heating section should reveal this page:



Similar to the heating schedules area, there is a large white field with a blue bar on the left side of the screen. This field can be populated with additional heating system names. The blue highlight is the selected system that can be renamed or altered with the information on the right side of the screen. Just above the name field, there is an “Add New Heating System” button. Pressing this once will create a new default heating system. The initial one that is created is named “Default,” as you can see atop the right side of the screen. Just below this name, you can choose the fuel type from a dropdown list of X fuel types. Once selected, the fuel cost can be entered into the window to the right of the selected fuel name. The units of fuel reflect the most commonly used unit of measure for that fuel type.

There are also many pictures of heating systems. Clicking on a picture once will enlarge that image and clicking on the enlarged image will close that picture. Select a heater type, a ventilation system, a heat delivery system, and provide a description of the system’s maintenance and age. These selections help describe the overall heating system’s efficiency, from flame to plant. Users can see the overall system efficiency value, from 0 to 100, in the lower right corner of this screen. This value is an estimate only and is based on a many measurements (energy audits) of several different greenhouses. However, it should be treated as an estimate only and is not a replacement for a complete energy audit performed by a professional greenhouse engineer. If you know your system’s overall heating system efficiency from such an audit, you can press the Override button in the lower right corner and enter your system’s efficiency.

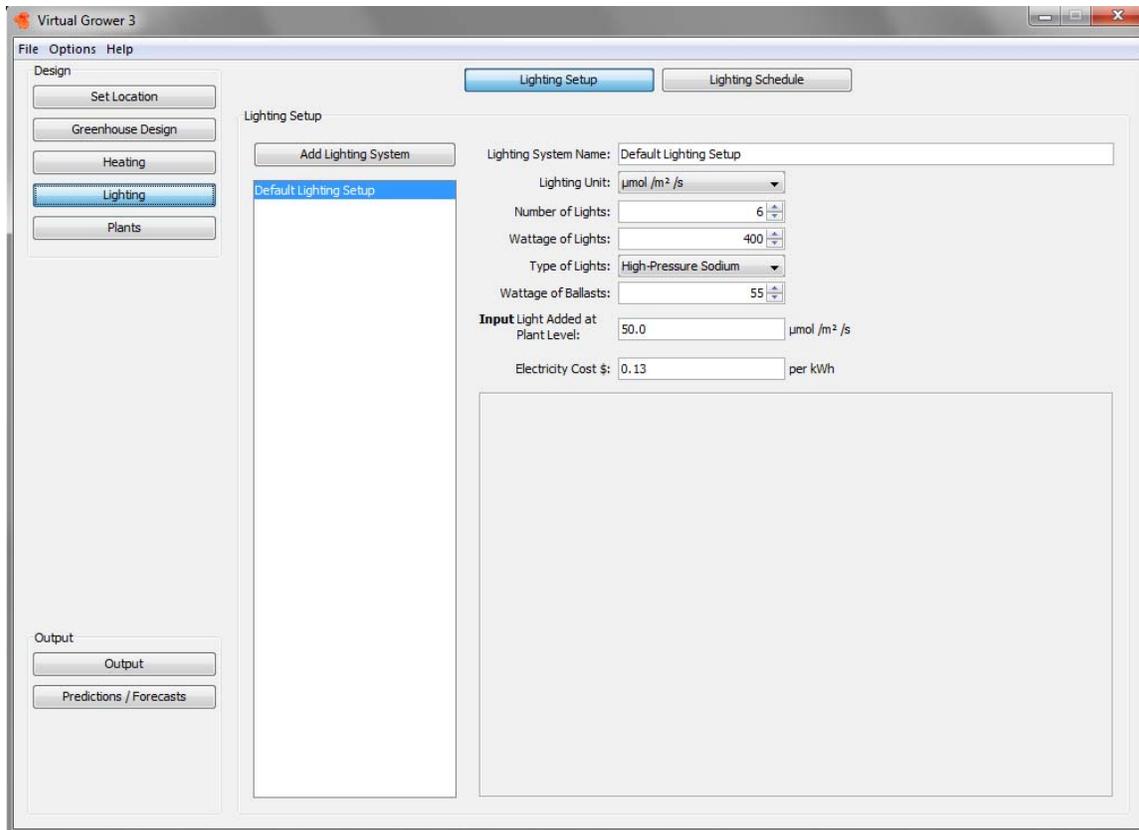
Often, a manufacturer will describe a heating system’s efficiency and include this in the specifications. This value is often a description of the combined heating system efficiency from heater type and ventilation. If you have such a number, press the override button located in the center of the page, just above the heat delivery section, and enter that value into the window. This will override the selections you made in the heater type and ventilation description. You will still need to describe the heat delivery, maintenance, and age for a complete system efficiency value.

Lighting

The use of electrical, supplemental lighting in greenhouses has long been important for greenhouse crop production. Interest in its use continues to expand given novel lighting strategies and technologies, the use of more diverse photoperiod-sensitive crop species, and the realization that light works in conjunction with temperature for enhanced crop quality. Challenges in implementing supplemental lighting systems include high initial start-up costs, high cost of electricity, replacement bulb and ballast costs, appropriate scheduling and management of day-length extension, providing uniform light across a growing area, and capturing waste heat from inefficient lamps. Since the release of Virtual Grower 2.5, the software has attempted to integrate the use of supplemental lighting from a variety of lamp types in a greenhouse system in

order for users to determine the value of using supplemental lighting against the cost of running such a system. We have focused initially on the challenges of ongoing electrical costs and appropriate management of day-length extension. We will continue to develop ways to include newer technologies such as LED lighting (currently not included in the software), uniform light distribution, and capturing waste heat from lamp systems.

Clicking on the “Lighting” button on the left side of the page should result in the following screen:



Lighting Setup

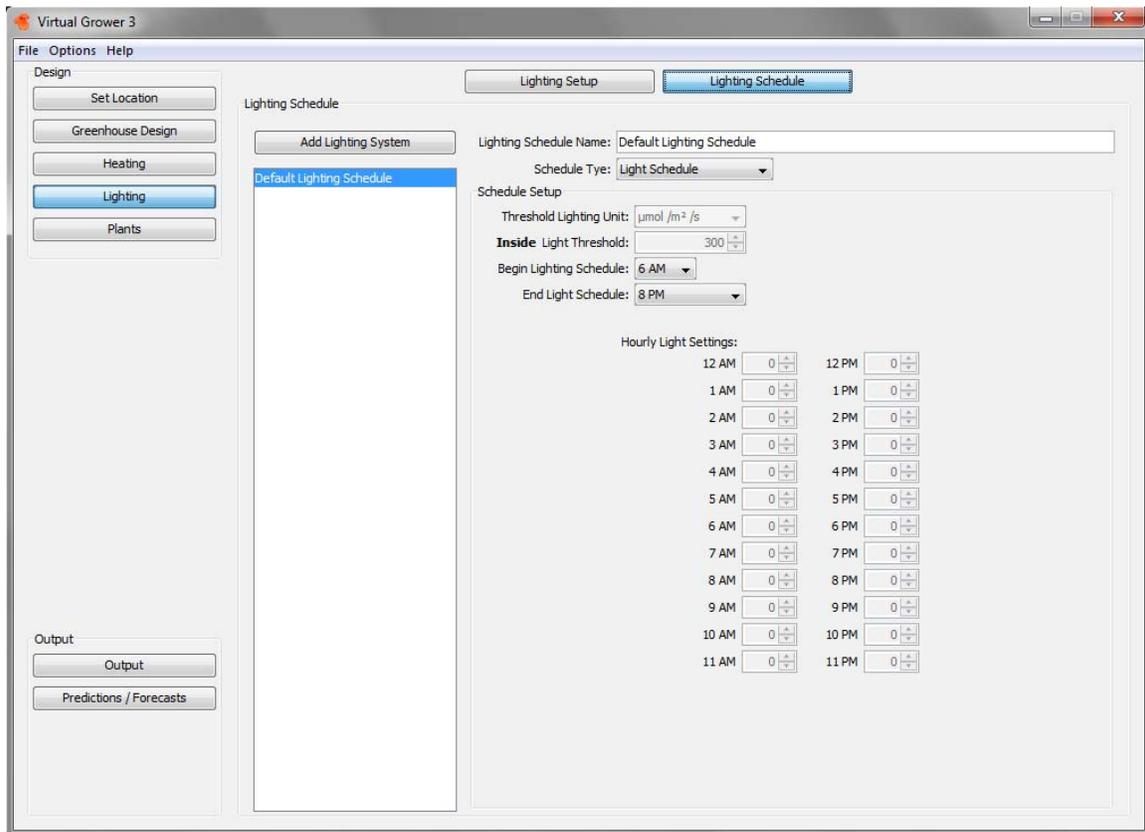
Similar to the areas in the “Heating” section, there is a large white field to the left of the center of the screen with a blue bar on top, just under a button labeled “Add Lighting System.” Upon opening the “Lighting” section, a default lighting system is loaded, labeled “Default.” The name can be changed at the top of the right section of the page in the field labeled “Lighting System Name.” A user can describe a lighting system in this area and apply this to a number of different greenhouses, or can describe several lighting systems and apply them to a few greenhouses.

To describe a lighting system, begin by selecting the units you are most comfortable with. The default settings are for $\mu\text{mol m}^{-2} \text{s}^{-1}$, an increasingly common way of measuring light for plant growth. The other possible units from the dropdown menu are footcandles, lux, W m^{-2} in photosynthetically active radiation (PAR) or W m^{-2} in total shortwave radiation (SW, from a pyranometer).

Enter the number of lights you have in a greenhouse (remember to include all lamps in a multi-span greenhouse, not just the lamps in a single span) and the lamp wattage (bulb wattage). Next, select the type of lamp. High Pressure Sodium is currently the most commonly used supplemental lamp in a greenhouse and is the default setting, but a user can select metal halide, incandescent, and fluorescent. Next, enter the ballast wattage (if unknown, leave as the default setting), and the light measured at the plant growing area – at plant level – that the lamps provide using the same units as listed above. Finally, enter the average cost of electricity in your area for the period of time you use lamps. Often, areas have off-peak prices that provide significant savings compared to traditional, peak usage rates. If this is unknown, your electric bill will have an average cost per kWh. This completes the Lighting Setup section.

Lighting Schedule

Pressing the button on the top right side of the screen in the Lighting section called “Lighting Schedule” should result in the following page:



Once again, this screen looks similar to several of the previous screens with a large white field to the left of the center of the screen that contains a blue highlighted lighting system name (default name is “Default”) below the button “Add Lighting System.” Pressing this button once will create a new lighting system, but the default one can also be modified.

Near the top of the right side of the screen, the lighting schedule name can be changed in the space provided. Below this, users can select the Schedule Type from the drop-down menu. The default category is a Light Schedule, which activates lights at a certain time during the day and turns them off at another time during the day. Those times can be selected in the area below, but only one on/off cycle is possible with this schedule selection.

Another option is the Hourly Threshold setting. This setting would utilize active feedback from environmental sensors inside the greenhouse that measure ambient light. If the light is below a set threshold, the lamps are activated. It would be necessary in the time columns in the bottom half of the right side of the screen to set the threshold at each hour. To ensure the lights do not come on at a particular time, set the threshold to zero (0). Higher values can be used to ensure the lamps are activated at that time. This setting allows for flexibility in when lamps come on as well as incorporating day-specific weather conditions; if there is a sunny day or a sunny time when supplemental light is especially needed, lamps and electricity can be conserved.

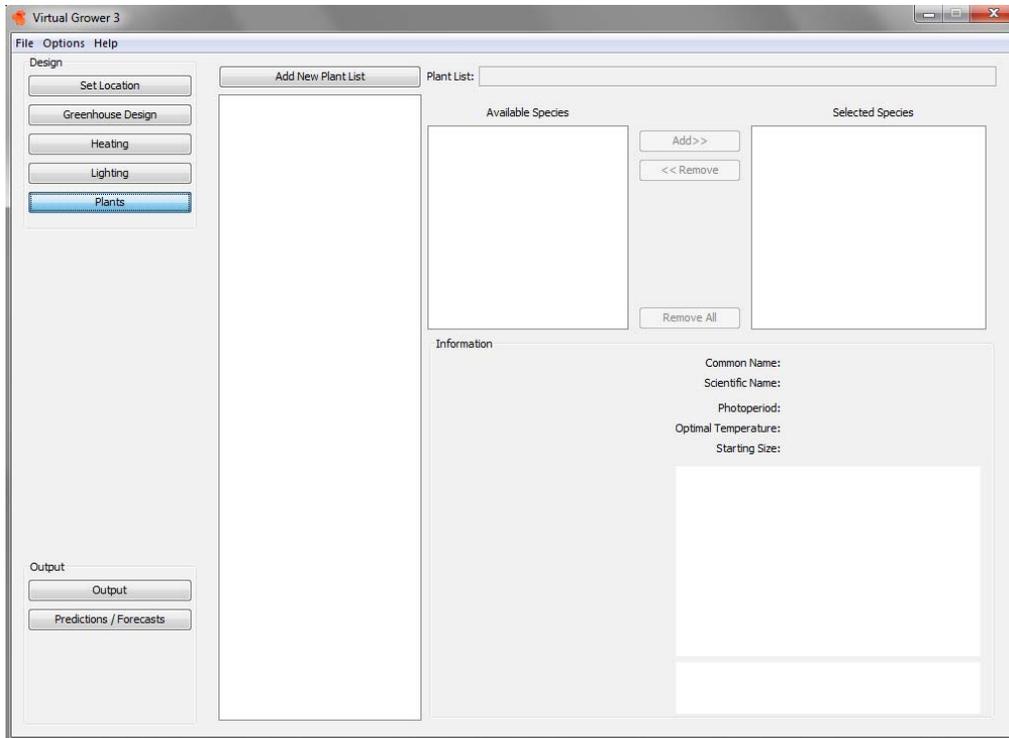
A third option is called “Hourly Light Schedule.” It is most similar to the “Light Schedule” option, but the “Hourly Light Schedule can be used to active or turn off lamps many times during the day. This approach ignores the prevailing sunlight availability, but can be done with simple timers and switches.

The final approach is called “Threshold” and is similar to the “Hourly Threshold” setting. This setting allows for an evaluation of interior light between a set period of time; if the light is below some threshold, lamps are activated. If the light surpasses the threshold during that same period, lights are turned off. Outside of the time boundaries, lamps are turned off. Both the time and light thresholds can be set on the right half of the screen, towards the middle.

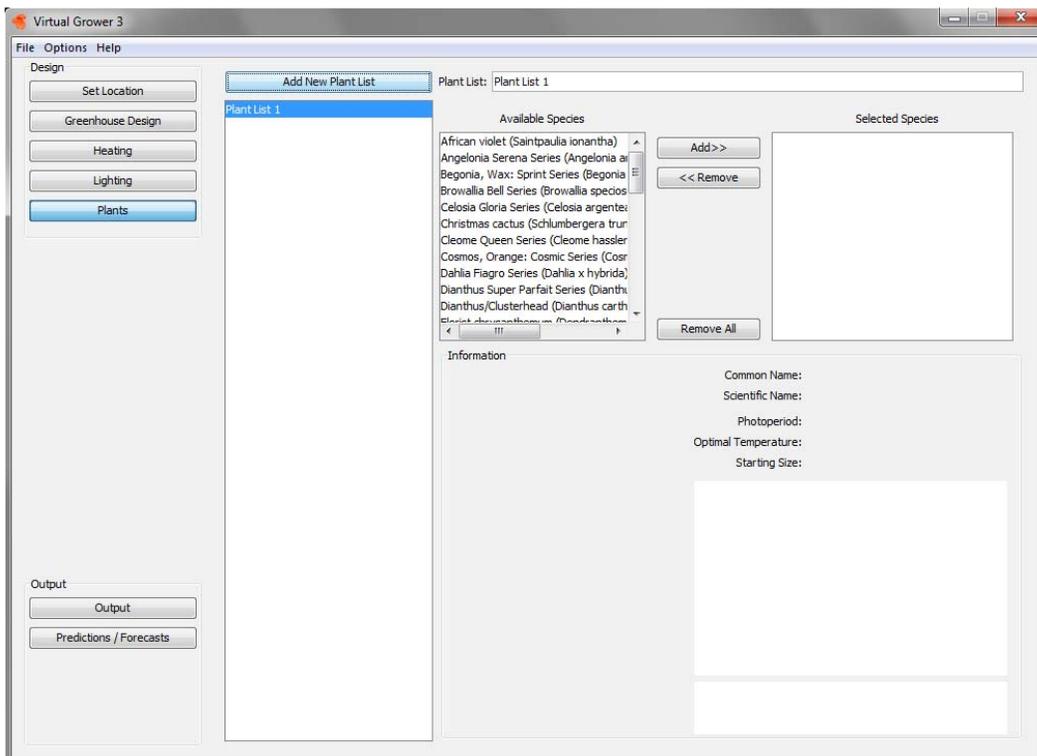
Plants

Starting with version 2.0, Virtual Grower users have been able to simulate plant growth (size) and development (time to flower) in their virtual greenhouses. Initially, a user was only able to simulate production based on their heating, lighting, and location settings. User comments to us have helped us create a new approach whereby users can find out when a plant should be planted given a particular finish date. We can still simulate “forward” and see how plants will grow in a given environment, but the new “lookback” approach helps scheduling for your unique greenhouse system.

By clicking on the “Plants” button on the left size of the screen, the following section should appear:

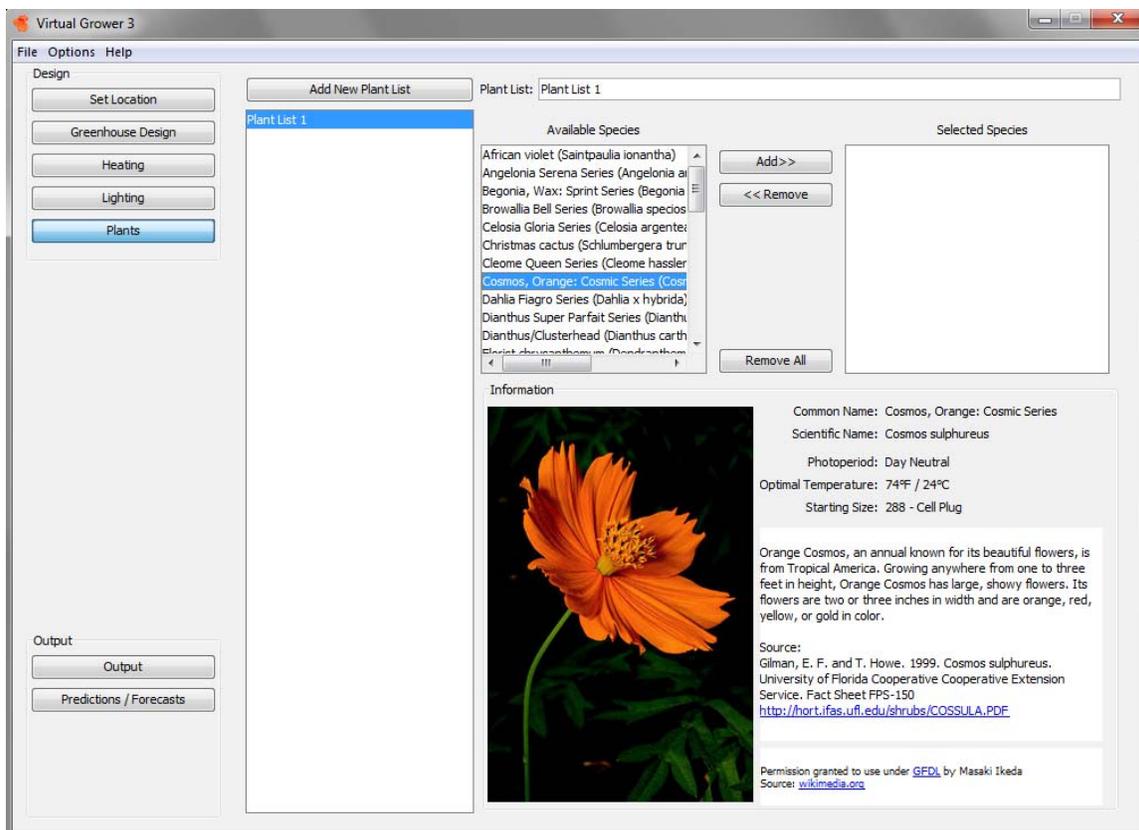


There are several blank white fields across this screen. The function of these fields is apparent after loading a plant list. At the top of the middle of the screen, there is a button named “Add New Plant List.” Clicking this button once results in the following screen:



You can now combine a group of plant species that are grown in a given area or across your greenhouses. The first, long field to the left of center, stretching from the top to the bottom of the screen, is the list of plant list names. The blue highlighted name is the plant list on which you are currently working. The default name is “Plant List 1.” To the right of the long plant list name field, there are two equally sized fields with the names at the top: “Available Species” and “Selected Species.” The Available Species field lists all possible species that we currently have in the database. We have added new species every year, and we will continue to add new ones as we discover their growth and development response to temperature and light (See Appendix 8 for more details). Creating a plant list to simulate involves clicking on a plant to highlight, clicking on the “Add>>” button, and repeating if necessary until all species in which you are interested are in the Selected Species window.

An added feature of Virtual Grower 3 is the additional information accompanying each species. When a species is selected in the Available Species List, pictures and more information appear below, as appears in this example with African violets below:



Not only is general information such as common and Latin names listed, but recommended photoperiod, temperature, and sources on the internet for additional information are provided. We feel this takes some of the guess work out of simulating the plants. But remember, this section is only to select what

you want to simulate. Simulation of plant size and time to flower is done in the Output section. See below for more description.

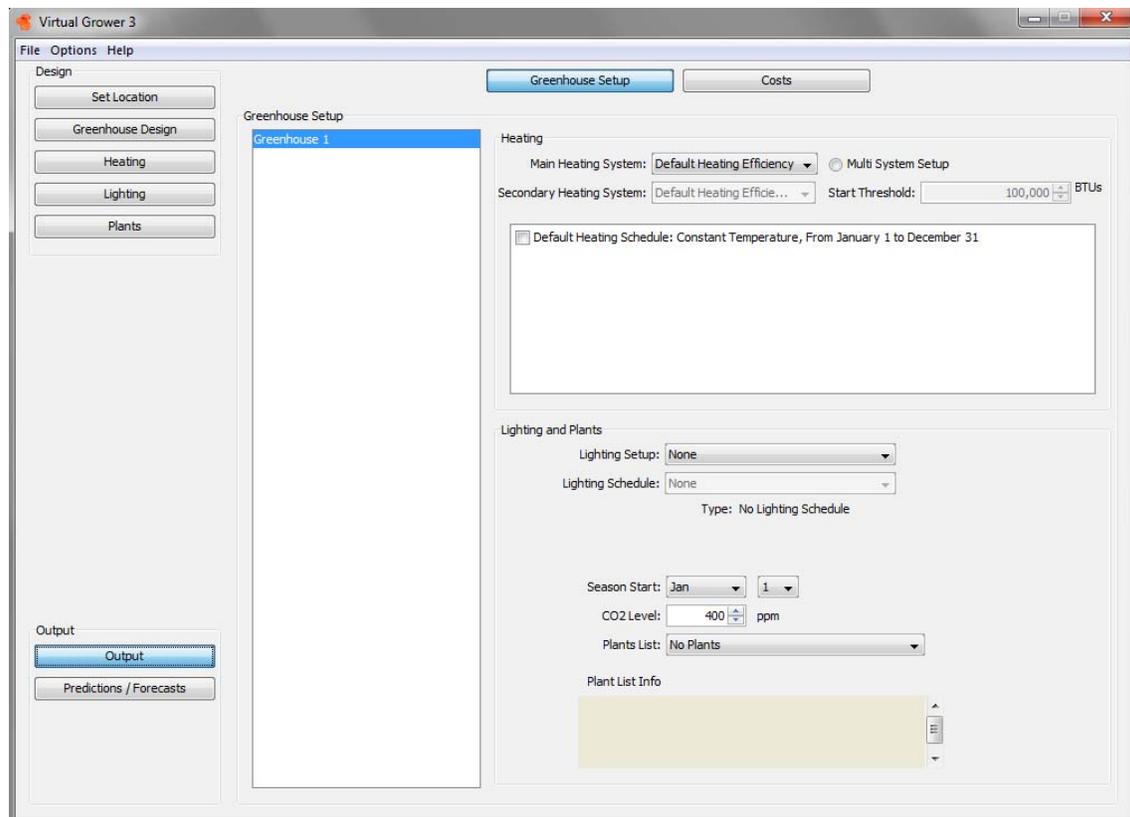
Saving / Loading

At any time during simulation or “constructing” your greenhouse, you can save the greenhouse setting from any page by clicking File<Save (top left corner of the screen) and naming your design file. This enables you to reload your greenhouse in other Virtual Grower sessions. Exiting out of the program at any point will also prompt you to save your settings.

If you would like to return to a previously saved simulation, go to File > Load and browse within your computer to find the proper .gsf file.

Output

Virtual Grower allows for great flexibility with building multiple, unique greenhouse structures, defining different heating systems, heating schedules, lighting systems and schedules, and finally growing different mixtures of plants. With that flexibility comes some complexity in assembling the mixture of all those schedules and systems into something that real numbers can be acquired. The initial page of the output section is the first place where many of those features can be assembled into a functional greenhouse system. Clicking once on the “Output” button in the lower left side of the screen should produce the following page:



The large field with the blue highlighted selection is the field that contains the greenhouses to be simulated. The selected greenhouse is the one that will be assigned heating and lighting systems and schedules along with plant lists, if desired. At the top right, there are two buttons called "Greenhouse Setup" and "Costs." The default page in the Output section is the "Greenhouse Setup" page.

Select the greenhouse you want to simulate or assign properties to (like heating systems and schedules, etc.) by clicking once in the Greenhouse Setup field to select your named greenhouse. To assign a heating system to that greenhouse, select one under the "Heating" heading for "Main Heating System" in the dropdown menu. Many greenhouses utilize a multi-stage heating system that relies upon one, high-efficiency system that runs most of the time, and during extreme temperature dips, a secondary, often times lower-efficiency system, to polish off the heating needs for a few hours. Virtual Grower 3 allows for this staging with a "Secondary Heating System" option, whose system can be chosen in the second drop-down menu after selecting the button "Multi System Setup" to the right of the Main Heating System. The user must also select the Start Threshold box to describe a Btu value at which point the secondary heating system will activate. That is, if the heating needs of your greenhouse exceed that Btu value in a given hour, the secondary heating system will activate and provide the rest of the heating needs up to the actual heating demand.

In the field just below the heating system selections, there is a list of heating schedules. Just to the left of each name, there is a small box. The box next to the schedule you want to use **MUST BE CHECKED** in order to activate that heating schedule. If no heating schedule is selected, there will be no output in either cost of operation or plant growth and development. If more than one heating schedule was described, they will appear in this field.

Below the heating schedule field, there is a "Lighting and Plants" section. This section allows you to apply a lighting system and lighting schedule to the desired greenhouses. Next to "Lighting Setup" and "Lighting Schedule" are drop-down menus that each contain the systems and schedules that were defined in the Design Heating or Design Lighting areas. If no lighting system needs to be simulated, select "None" in the "Lighting Setup" drop-down menu.

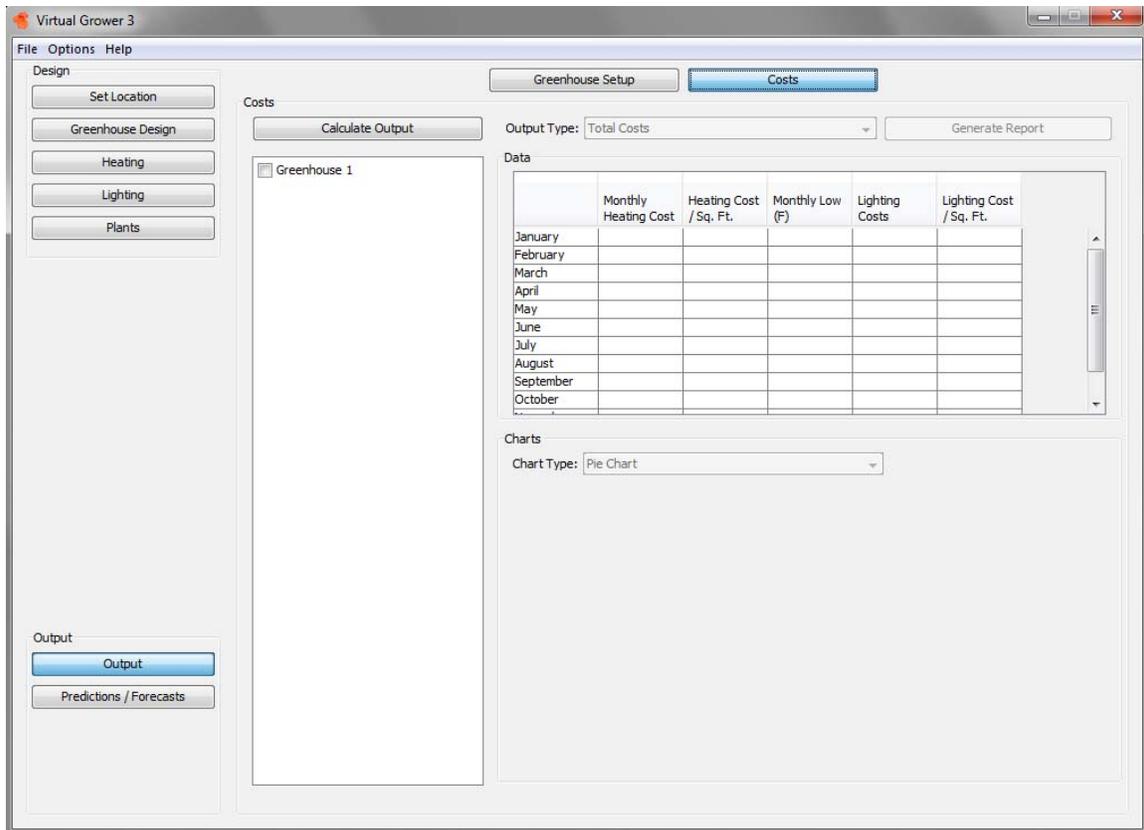
Below the lighting assignment section, there is the plant growth and development (scheduling) section. Select the date that the growing season begins or when the plants will be started in the greenhouse. This date must be on or after the start of the heating schedule selected in the field above. Once selected, choose a CO₂ level that is used inside the greenhouse. If no supplemental CO₂ is selected, enter a value of between 350 and 400 ppm CO₂ (default value = 400 ppm). Finally, choose a plant list from the drop-down menu next to the "Plant List" entry. A few details about your selected plant list will appear in the bottom field for confirmation purposes. Any changes to this plant list must be made in the Design Plants area accessible with the buttons on the left side of the screen.

While complex, this approach allows a user to assign heating and lighting systems and schedules as well as plant lists to a given greenhouse streamlines simulations since a single heating or lighting system can be applied to any

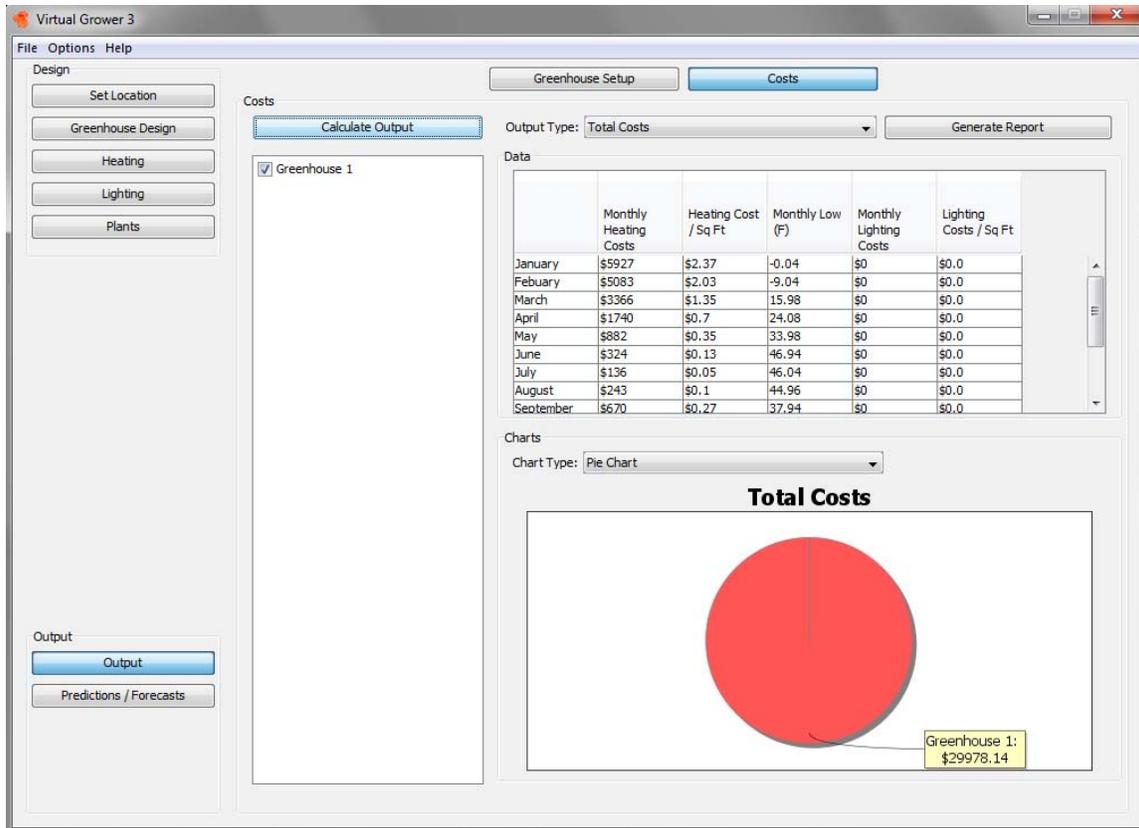
number of greenhouses without having to recreate each heating and lighting system for each greenhouse individually, as was done in earlier versions of the software. Once selected, output (costs, timing) can be simulated.

Costs

Clicking once on the “Costs” button within the Output section should reveal the following screen:



Clicking once in the empty box next to the greenhouse name(s) within the greenhouse name field will activate or select those greenhouses for simulation. Once selected, press the “Calculate Output” button near the top, center of the screen. After a moment (less than a second, typically), costs of heating and lighting that/those greenhouses are calculated and the table on the right side of the screen is populated. The following screen is an example of what it may look like (actual screen depends on number of greenhouses being simulated, location, etc.):



Monthly heating and lighting costs are displayed along with costs per square foot per month. The middle column displays the monthly low temperature event from the database. The lower part of the screen displays a graph of total costs including the sum of heating and lighting for all simulated greenhouses.

This version of Virtual Grower allows for the differential display of costs using two different options. At the top of the screen, there is an “Output Type” drop-down menu, which includes “Total Costs,” “Costs per Greenhouse,” and “Plant Growth.” Above the graph, there is a “Chart Type” drop-down menu, which includes “Pie Chart,” “Line Chart (hourly),” and “Line Chart (daily).” Selecting each of these options will alter the visual display of the graph at the bottom of this page.

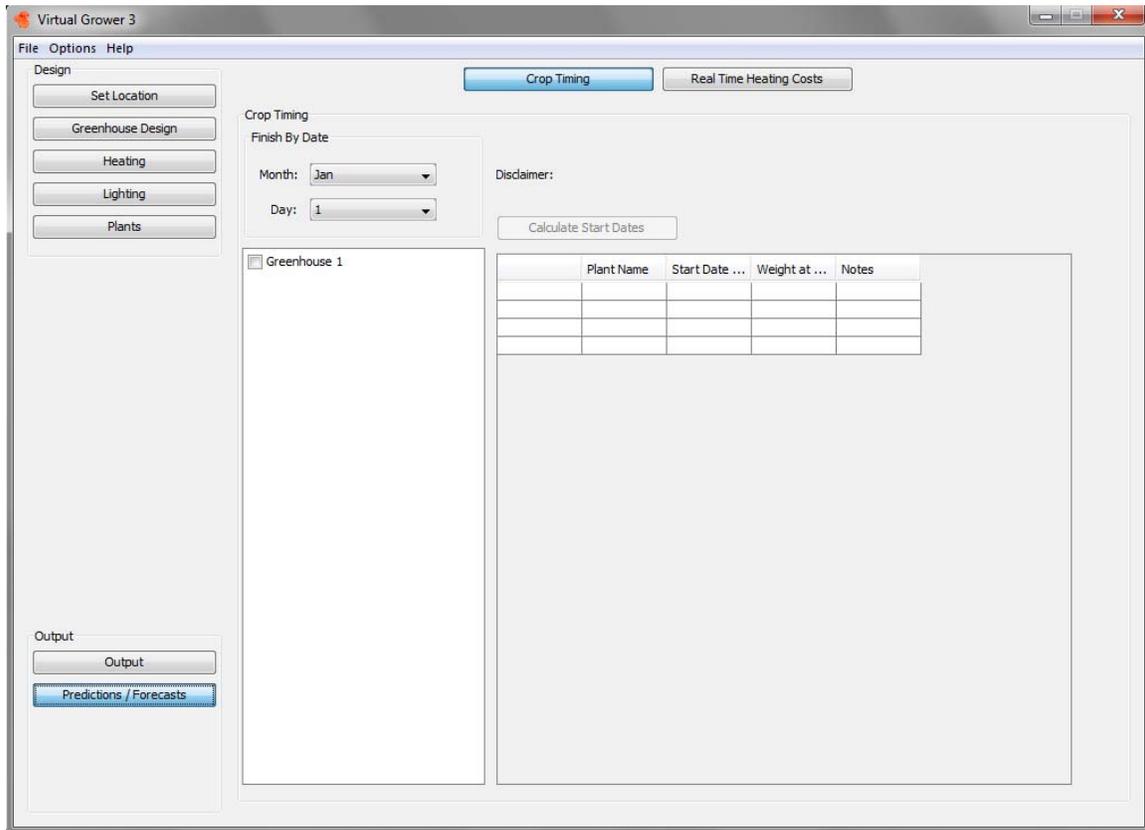
The final button on this page is the “Generate Report” button on the upper, right side of the screen. Clicking this button once will automatically select all greenhouse settings and output and allow the user to save it in a text file. This file can be opened in word-processing or spreadsheet software.

Predictions/Forecasts

User feedback since the initial release of the software has stimulated the development of improved predictions and forecasts. For example, with plant growth, many users have expressed a desire to learn when they should start plants given a finish date at a particular week in the year. Earlier versions of the software could only provide that information through iterative, repeated

simulations with different starting dates to “land on” the desired finish date. Alternatively, the heating section can provide information about “typical” years, but real-time forecasting is desirable for extreme weather events (cold snaps, for example). This version of Virtual Grower attempts to address these needs in this section.

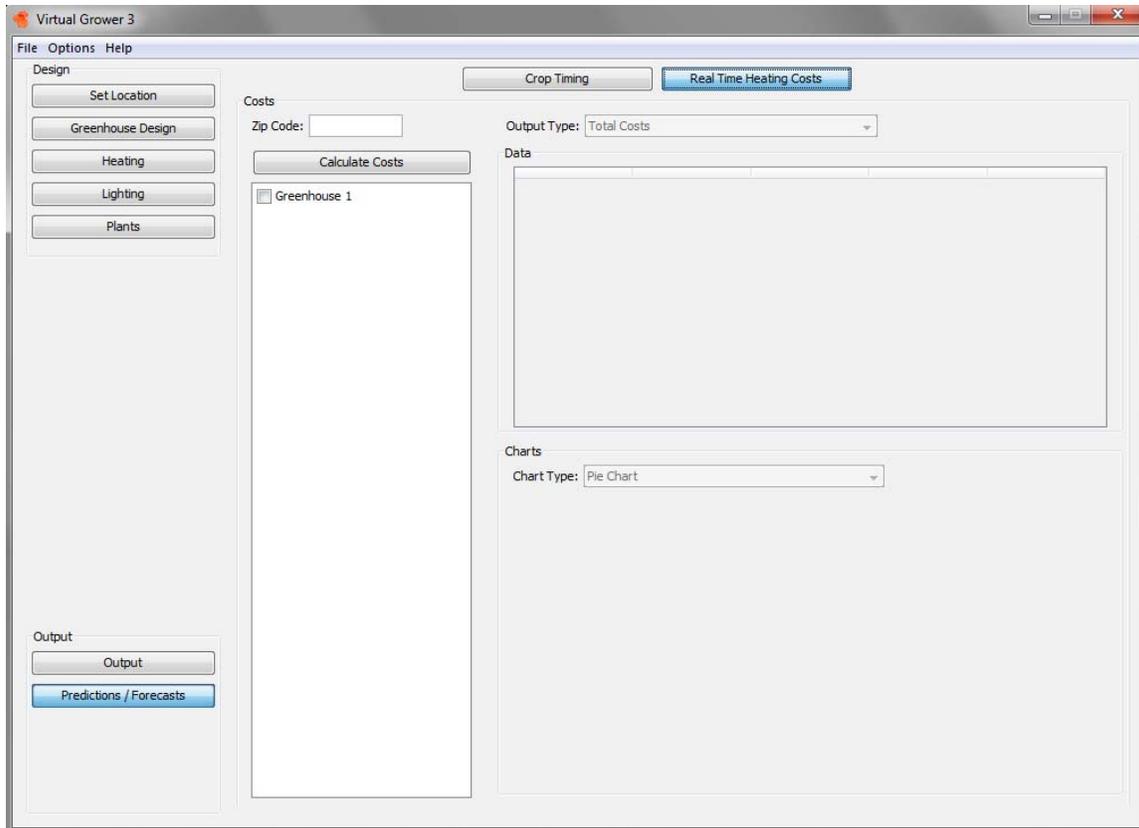
Pressing the Predictions/Forecasts button once should result in the following screen:



On this page, a user can enter a desired finish date, run the simulation, and predict the date that the user should start their crops from seedling/plug stage in a typical year based on their greenhouse settings. To do so, select a month and day in the drop-down menus near the top, left of the screen, select a greenhouse to activate or simulate within, and click the “Calculate Start Dates” button once. Doing so will populate the table on the right side of the screen with the species in your plant list (selected in the Plants section), list the predicted start date, expected size at flowering, and any additional information or warnings about those crops in that simulation. If desired, a new finish date can be entered, additional simulations can be run, and those new start dates and plant sizes will be appended to the original information from those simulations.

Real Time Heating Costs

Clicking once on the real-time heating costs button on the top of the Predictions/Forecasts section should result in the following screen:



This page looks and functions similar to the Output-Costs page. At the top middle of the page, there is a space to enter your zip code. After one is entered and a greenhouse is selected from the greenhouse list field, click once on the Calculate Costs button. After a few seconds, the data field is populated and a chart appears on the bottom half of the right side of the screen. These data describe the predicted costs of heating your designed greenhouse at your zip code location for the next three days. The way this page functions is that the program accesses the weather forecast at your location from the website forecast.weather.gov and compares it to greenhouse set points. For this reason, you must have an active internet connection in order for this feature to work properly. Additionally, the feature only works for the “lower 48” US states.

The data is only as good as the weather forecasts. It is more accurate also if you are already heating your greenhouse (i.e. not in the summer) since no heat storage from cement, structure, or other materials is included in these short-term calculations. No lighting estimates are included since weather forecasts do not include radiation values, but instead include qualitative descriptions such as partly sunny, mostly cloudy, etc.

Metric / English Units

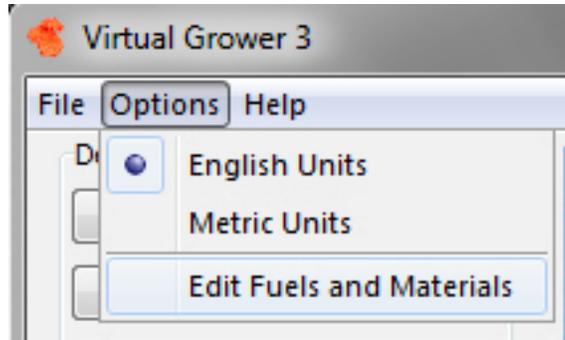
The units of measurement can be changed between English and Metric by going to the Options drop-down menu in the upper left corner of all screens.

Help

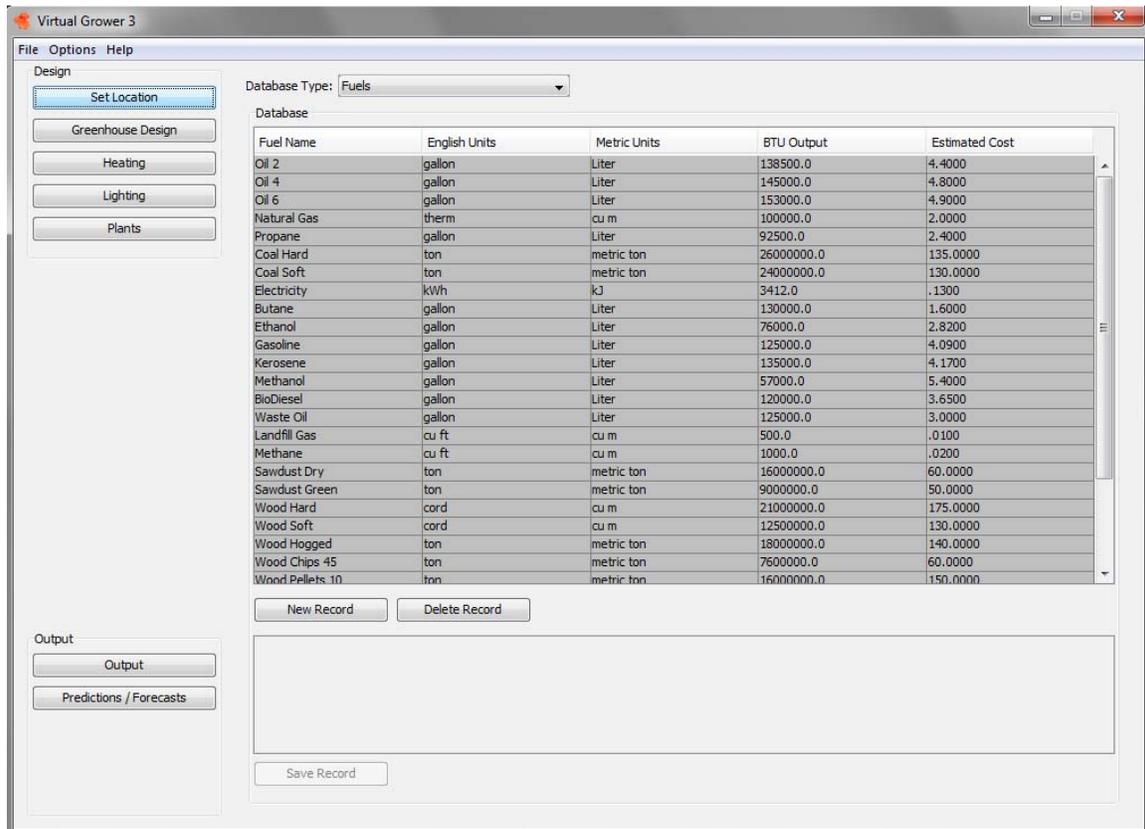
An electronic version of this manual can be found in the Help window as well as credits, acknowledgements, and other useful references. If you have any questions or comments and can not find the information in this manual or in the About section, feel free to contact us at USDA-ARS@utoledo.edu.

Edit Fuels and Materials

In the Options drop-down menu in the upper left corner of the program, you can select to add or alter materials and fuels:



Selecting this option will reveal the following screen:



In this section, users can add different fuels or materials for subsequent testing in Virtual Grower. At the top of the screen, select either Fuels or Materials to alter from the drop-down menu labeled "Database Type." Based on this selection, the middle area will be filled with the current information for fuels or materials. Just below this field, there are two buttons labeled "New Record" and "Delete Record." Because the pre-loaded fuels and materials are protected, there is no threat to accidentally delete any entries from the default database. Clicking the New Record button when the database type is selected for fuels will show a new row of information in the field just below the New Record button. This row will have the opportunity to load a fuel name, unit of measurement, BTU output or value, and estimated/default cost. When these are completed, click the "Save Record" button and the user will have the opportunity to select this new fuel in the heating simulations.

Alternatively, clicking the New Record button when the database type is selected for materials will show a new row of information in the field below the New Record button that allows for material name, U-value, light transmittance, air exchange value, and options for material type. Clicking once inside the material type cell will reveal a drop-down menu of choices between sides and roof, kneewall, and energy curtain. Once completed, click the "Save Record" button and users can test the new material in the greenhouse design and heating portions of the program.

Some Assumptions of Virtual Grower 3.0

Weather at a location

The weather information is not average values for a period of time, but typical or representative values for that date and time. This means that at your location, the month of January used in the program is from 1974 and the month of February is from 1982. Those years were chosen because they represent “typical” months at that location.

An alternative method of calculating a building’s heat requirements is the use of a “Heating Degree Day” model. This method bases heat needs on the average temperature during a day. If the average temperature is below 65 F (18 C), heating is required. A list of heating degree days for different locations can be found at www.nrcc.cornell.edu/ccd/nrmhdd.html. The heating degree days that Virtual Grower predicts and this database are in close agreement (typically less than 1%). On some days, however, the heating degree day model predicts no heat is needed when Virtual Grower would predict some heat is needed. For example, assume your greenhouse has a set point of 65 F. If a location (hypothetical) has an average temperature of 65 F, has a 12-h day of 75, and a night time of 55, Virtual Grower would heat the house for 12 hours (during the night) and the heating degree day model would predict no heat is needed.

Greenhouse isolation

Currently, each greenhouse is treated as a stand-alone structure with no shared walls with other houses or structures. This would influence heat loss or gain and potentially have a significant impact on the overall costs of heating your greenhouse ranges.

Humidity

Currently, all calculations are assuming dry air. This assumption greatly shortens the calculation time, but would ignore issues such as latent heat (evaporation and condensation) and changes in humidity outside the greenhouse causing changes inside the greenhouse. In Version 2.0, a multiplier was inserted (see Appendix 5, Heat Gain by Solar Radiation) to account for some of the effect due to evapotranspiration. Still, with a single multiplier, the effect of latent heat is assumed constant.

Errors? Questions? Problems? Suggestions?

Contact us (USDA-ARS@utoledo.edu). This is a work in progress and with your help, we can improve Virtual Grower and it can better suit your needs. Please give us feedback – WE WANT TO HEAR FROM YOU!

Appendix 1: Fuel energy content used in Virtual Grower 3.0

Fuel Type	Energy (btu)	Unit for energetic amount
Fuel Oil #2	138,500	Gallon
Fuel Oil #4	145,000	Gallon
Fuel Oil #6	153,000	Gallon
Natural Gas	100,000	Therm
Propane	92,500	Gallon
Hard Coal	26,000,000	Ton
Soft Coal	24,000,000	Ton
Electricity	3,412	kWh
Methane	1,000	ft ³
Methanol	57,000	Gallon
Landfill Gas	500	ft ³
Butane	130,000	Gallon
Ethanol	76,000	Gallon
Kerosene	135,000	Gallon
Waste Oil	125,000	Gallon
Biodiesel	120,000	Gallon
Gasoline	125,000	Gallon
Soft Wood	12,500,000	Cord
Hard Wood	21,000,000	Cord
Hogged Wood	18,000,000	Ton
Sawdust (green; 45% moisture)	9,000,000	Ton
Sawdust (dry)	16,000,000	Ton
Wood Chips	7,600,000	Ton
Bark	9,750,000	Ton
Wood Pellets (10% moisture)	16,000,000	Ton
Rubber Pellets	33,000,000	Ton
Plastic	19,000	lb
Corn Shells	16,000,000	Ton
Corn Cobs	16,500,000	Ton
Switchgrass	11,625,000	Ton

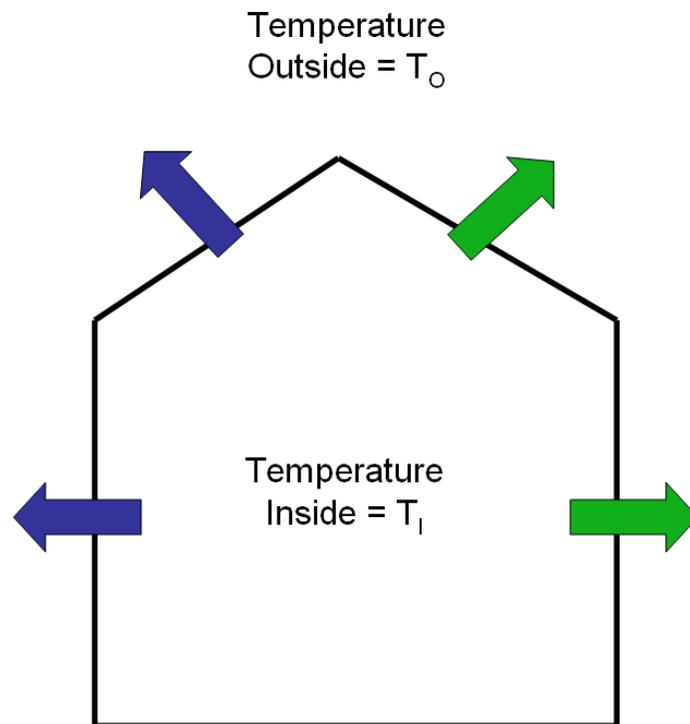
Values were obtained from Bartok, J.W. Jr., 2005, floriculture fact sheet from U Mass Extension:

http://www.umass.edu/umext/floriculture/fact_sheets/greenhouse_management/jb_fuels.htm

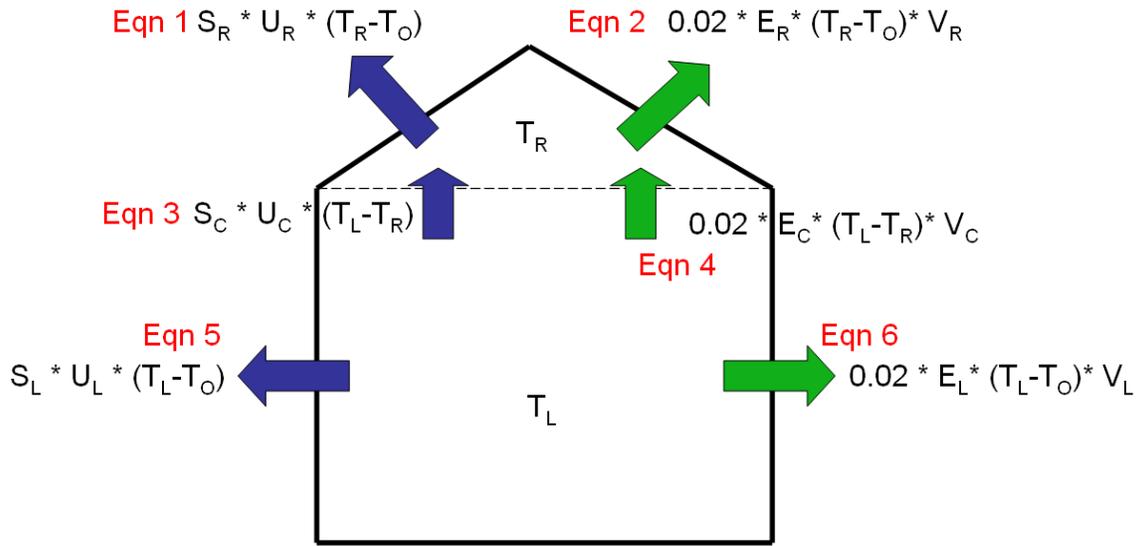
Appendix 2: Energy curtain assumptions

The energy curtain feature of Virtual Grower is an approximation that does not rely on a constant offset or “fudge factor” created by changing the energetic properties of the roof by a constant amount. The impact that a curtain material makes through its inherent insulation value as well as its ability to inhibit air mixing from the upper section to the lower is accounted for in the calculations. To illustrate more specifics on how the curtain calculations were conceived and executed, read the description below.

We have attempted to place a division between the upper and lower sections of a greenhouse in software and treat the greenhouse as two parts if a curtain is in place rather than one greenhouse with different heat loss/gain characteristics. Conceptually, we consider that a greenhouse is losing heat at night from the roof and sides through conduction (blue arrows) and convection (green arrows; for simplicity of the drawing, we show one type of energy loss through a single side of the greenhouse) if the temperature inside (T_i) is less than the temperature outside (T_o).



If an energy curtain is added, the greenhouse is still losing heat from the sides and the roof. However, since the volume of greenhouse above the energy curtain is not actively being heated, there is another heat flow from the lower section to the upper section such that the temperature inside the lower part (T_L) is higher than the temperature of the upper section (T_R).



If T_L is maintained at the setpoint, the temperature in the upper section (T_R) will reach an equilibrium between T_O and T_L , which will depend on T_O , T_L , well as the thermal properties and air exchange of the roof and energy curtain as well as the sizes of the roof and energy curtain. Mathematically, this is:

- 1) Roof Heat Loss = $[S_R * U_R * (T_R - T_O)] + [0.02 * E_R * (T_R - T_O) * V_R]$
- 2) Heat Loss over the Curtain = $[S_C * U_C * (T_L - T_R)] + [0.02 * E_C * (T_L - T_R) * V_C]$

When S_R is the surface area of the roof, U_R is the U-value of the roof material, E_R is the air exchanges due to leakage or infiltration through the roof, V_R is the volume of air above the energy curtain, S_C is the surface area of the energy curtain, U_C is the U-value of the energy curtain, E_C is the air exchanges due to leakage or infiltration through the energy curtain, and V_L is the volume of air below the energy curtain. Eqn 5 and 6 in the figure above will be defined later. To get the temperature above the curtain to stabilize, the amount of heat gained through the curtain from the heated greenhouse below and the amount of heat lost to the outdoors must be equal:

$$3) [S_R * U_R * (T_R - T_O)] + [0.02 * E_R * (T_R - T_O) * V_R] = [S_C * U_C * (T_L - T_R)] + [0.02 * E_C * (T_L - T_R) * V_C]$$

Solve for T_R :

$$[(S_R * U_R * (T_R - T_O)) + (0.02 * E_R * (T_R - T_O) * V_R)] - [(S_C * U_C * (T_L - T_R)) + (0.02 * E_C * (T_L - T_R) * V_C)] = 0$$

$$(S_R * U_R * T_R) - (S_R * U_R * T_O) + (0.02 * E_R * V_R * T_R) - (0.02 * E_R * V_R * T_O) - (S_C * U_C * T_L) + (S_C * U_C * T_R) - (0.02 * E_C * V_C * T_L) + (0.02 * E_C * V_C * T_R) = 0$$

$$(S_R * U_R * T_R) + (0.02 * E_R * V_R * T_R) + (S_C * U_C * T_R) + (0.02 * E_L * V_L * T_R) = (S_R * U_R * T_O) + (0.02 * E_R * V_R * T_O) + (S_C * U_C * T_L) + (0.02 * E_C * V_C * T_L)$$

$$T_R * [(S_R * U_R) + (0.02 * E_R * V_R) + (S_C * U_C) + (0.02 * E_L * V_L)] = (S_R * U_R * T_O) + (0.02 * E_R * V_R * T_O) + (S_C * U_C * T_L) + (0.02 * E_C * V_C * T_L)$$

$$T_R = [(S_R * U_R * T_O) + (0.02 * E_R * V_R * T_O) + (S_C * U_C * T_L) + (0.02 * E_C * V_C * T_L)] / [(S_R * U_R) + (0.02 * E_R * V_R) + (S_C * U_C) + (0.02 * E_L * V_L)]$$

All variables are known or estimated and therefore, T_R can be calculated (see Appendix 3 for U-values of materials). In Virtual Grower, the energy flows are calculated every hour based on the historical database for each location so T_R changes each hour based on the outside temperature (and if there are any custom schedules used for that greenhouse).

TOTAL ENERGY FLOW WITH ENERGY CURTAINS

Once T_R is calculated, hourly heat loss from a greenhouse is the result of the sum of Eqn 1, Eqn 2, Eqn 5 and Eqn 6 (from figure above), where S_L is the surface area of the lower section, U_L is the U-value of the materials on each wall of the lower section, E_L is the air exchange rate of the lower section, and V_L is the volume of the lower section.

CAUTION:

This calculation does not take into account the energy flux from radiation. Energy losses from this component may be significant and could cause the assumptions used in the energy curtain calculations for Virtual Grower 3.0 to over-estimate the impact of having energy curtains. Furthermore, we continue with the assumption of dry air for all air/heat fluxes and do not factor in the impact of heat storage of the ground and materials.

The energy curtain feature is only activated at night, which is based on your location in the country and not by heating schedule. Functionally, the curtain acts as if it instantly snaps shut at sundown then instantly snaps open at dawn.

Appendix 3: U-values for materials

Material	U-value (Btu hr ⁻¹ °F ⁻¹ ft ⁻²)	Light Transmittance (%)
Glass	1.13	0.75
Glass double layer	0.65	0.70
Fiberglass	1.00	0.75
Corrugated polycarbonate	1.20	0.75
Polyethylene	1.15	0.65
Polyethylene double layer	0.70	0.60
Polycarbonate bi-wall	0.65	0.60
Polycarbonate triple-wall	0.58	0.56
Acrylic bi-wall	0.65	0.60
IR film	1.00	0.65
IR film double layer	0.61	0.60
Solid insulation foam	0.23	0
Concrete Block	0.51	0
Poured Concrete	0.75	0
Insulated Concrete	0.13	0
Energy Curtains		Air Infiltration (leakage per hour)
Mobile air curtain	0.68	1.5
Stationary air curtain	0.54	1.5
White spun bonded polyolefin film	0.51	0.7
Grey spun bonded polyolefin film (light)	0.56	1.5
Clear polyethylene film	0.45	0.4
Black polyethylene film	0.48	0.4
Grey spun bonded polyolefin film (heavy)	0.43	1.0
Aluminum-clear vinyl fabric	0.40	0.7
Aluminized fabric	0.39	0.9
Aluminum-black vinyl fabric	0.63	0.7
Double layer spun bonded polyester	0.53	1.0

Values were obtained from Bartok, J.W. Jr., 2005, floriculture fact sheet from U Mass Extension:

http://www.umass.edu/umext/floriculture/fact_sheets/greenhouse_management/jb_fuels.htm

and Aldrich, R.A. & J.W. Bartok Jr. 1994. Greenhouse engineering. NRAES. Ithaca, NY.

Appendix 4: How the maximum BTU output is calculated

This feature from the Costs tab is designed to assist in boiler or heater sizing. Simply, the value reported is the largest heat loss rate for your greenhouse design, location, and heat schedule.

The program can calculate the heat loss for a greenhouse for every hour in a year or other selected time frame based on your heating schedule. After calculating heat flow for each hour, the largest number is reported. This number is also based on the number of greenhouses selected, so if more than one greenhouse was designed in the design phase, the maximum BTU output reported is assuming if all selected greenhouses are run off a single heater/boiler. When using this feature, remember that the values are based on TYPICAL weather at that location and does not estimate very cold weather events (i.e. a cold snap or inversions). Therefore, you may need to add more BTU to “size up” your boiler for the greenhouse to account for those events. This decision is based on the weather and also the grower’s risk tolerance for extreme weather events.

Appendix 5: Calculating Energy Flow

There are two basic equations that Virtual Grower uses to calculate energy flow through a greenhouse. One is for conduction, the transfer of heat through the structure of the greenhouse, and the second is for convection, the transfer of heat by mixing cooler outside air with warm greenhouse air. When calculating the heat loss for any greenhouse structure, both of these equations are taken into account, at least to some degree.

The particular equations we used are from Aldrich and Bartok, 1994, Greenhouse Engineering, NRAES publication 33, and are outlined below:

Conduction

To calculate conduction over any greenhouse surface, four values are used; the temperatures on either side of the surface (usually the temperature set point of the greenhouse and the current temperature outside), the area of the surface, and a constant known as the U-value of the surface material (See Appendix 3 for U-values). The U-value represents a typical amount of heat energy that will cross a certain area of the material, per degree difference between the inside and outside temperatures. By multiplying these values together, the amount of heat per hour that is lost to that surface can be found. For example, if a small greenhouse was set to 65°F and the outside temperature was 45°F, a 100 ft² sheet of glass with a U-value of 1.13 BTU/ft² -°F-hour, then the amount of heat lost over the sheet of glass would be:

$$(65^{\circ}\text{F} - 45^{\circ}\text{F}) \cdot 100 \text{ ft}^2 \cdot 1.13 \text{ BTU/ft}^2 \text{ -}^{\circ}\text{F-hour} = 2260 \text{ BTU/hour}$$

Lastly, this value can be multiplied by a correction factor to account for the effects of wind. See Appendix 6 for a list of the correction factors used.

Convection

To calculate convection for any particular greenhouse, four values are used; the temperatures on the inside and outside of the greenhouse, the volume of air within the greenhouse, and a correction factor representing the relative leakiness of the greenhouse structure. By multiplying the difference between the two temperatures by the volume and the correction factor, an estimate of heat loss can be obtained. For example, if the temperature outside was 45°F, the temperature inside was maintained at 65°F, the volume of the greenhouse was 5000 ft³ and the greenhouse was assumed to have an average 'leakiness' (correction factor = 0.02 BTU/ft³-°F-hour), the amount of heat lost per hour due to convection would be:

$$(65^{\circ}\text{F} - 45^{\circ}\text{F}) \cdot 5000 \text{ ft}^3 \cdot 0.02 \text{ BTU/ft}^3 \text{ -}^{\circ}\text{F-hour} = 2160 \text{ BTU/hour}$$

As with conduction, a correction factor to account for the effects of wind can be applied – see Appendix 6.

Totaling Heat Loss

To find an estimate of the heat energy lost for an entire structure, conduction is calculated for each wall, each portion of the kneewall, and for the

roof, and convection is calculated for the whole structure. Adding the results together gives us our estimate.

Heat Gain by Solar Radiation

For every location in Virtual Grower, there is a database of expected solar radiation which can be used to find an estimate of how much heat the greenhouse will gain from the sun. For our estimate, we simply multiply the amount of light energy hitting per square foot of ground space by the total footprint of the greenhouse. Not all the energy from the sun will heat the greenhouse; reflection off the greenhouse surfaces and evapotranspiration will dramatically decrease the amount of energy or heat from the sun. To compensate for this, Virtual Grower assumes that about 33% is reflected from the greenhouse materials and about 50% of the remainder is used for evaporating water from plants and substrate surfaces. This means that only 33% of the sun's energy heats the greenhouse. To estimate heat gain through solar radiation, Virtual grower multiplies that amount of light energy hitting per square foot of ground space, 0.33 (the amount of light making it into the greenhouse), and by the total footprint of the greenhouse.

Net Heat Change in the Greenhouse and Heating Costs

Using the above calculations, Virtual Grower calculates the net amount of heat energy leaving or entering the greenhouse. This is simply done by adding the total heat lost to conduction and convection to the heat gained by solar radiation. If the result is negative, i.e., the greenhouse is cooling off, the number of BTUs lost is assumed to be the number of BTUs added to the greenhouse by its heaters, to keep it at its current temperature. If the number is positive, it is assumed that the greenhouse is being cooled somehow and that no fuel is being burned to heat the structure.

To calculate a cost for heating the greenhouse, the number of BTU's being lost is divided by the amount of heat gained from burning one unit of fuel (whichever fuel is selected), adjusted for the given heater efficiency. This gives us the amount of fuel needed to keep the greenhouse up to temperature. Finally, the cost to heat the structure is calculated by multiplying the units of fuel burned by the cost per unit specified for that greenhouse.

Using Energy Curtains

When an energy curtain is being used in a greenhouse, the amount of heat lost to the structure is calculated somewhat differently. Refer to Appendix 2 for an explanation for how this is done.

Appendix 6: Correction factors used in Virtual Grower

Correction factor	Conditions	Value
Wind speed for conduction and convection	wind < 15 mph	1
	15 mph < wind < 20 mph	1.04
	20 mph < wind < 25 mph	1.08
	25 mph < wind < 30 mph	1.12
	30 < wind	1.16

Values were obtained from Bartok, J.W. Jr., 2005, floriculture fact sheet from U Mass Extension:

http://www.umass.edu/umext/floriculture/fact_sheets/greenhouse_management/jb_fuels.htm

Appendix 7: Calculating plant growth and development

Crop growth and development depends in large part on light and temperature. Virtual Grower allows for a great deal of control over temperature and relies on the weather database for light. For the most rapid rate of development, many crops require an inductive photoperiod; without this photoperiod, plants will fail to flower or development will be significantly delayed, yet may continue to grow vegetatively. For simplicity only, we have decided to assume that the photoperiod required for proper development (i.e., flowering) for each crop is being met. Therefore, for Virtual Grower, crop development will only depend on the average temperature and light levels during the cropping schedule. For growth, we have used a single leaf photosynthesis model and allow light to drive growth. In this model, however, leaves must intercept that light in order to grow. Therefore, some estimate of leaf expansion must precede estimates of photosynthesis and biomass gain.

In the following section, more detail is given for the assumptions and calculations for plant development and growth in Virtual Grower. At the end of this section, many references we have found useful are reported, if you would like to go into more detail on crop modeling.

Light

The unit of light that is used for Virtual Grower is the Daily Light Integral or DLI, measured in moles of photons per square meter per day. It is the total or integrated light during one day that a plant can use. The weather database used in this software reports total radiation averaged for each hour, in Watts per square meter. This is converted to photosynthetically active radiation (PAR; units are micromoles of photons per square meter per second) by dividing total radiation by 0.47. The result is converted to moles of photons per square meter per hour by multiplying by a factor of 3600 (seconds per hour) and dividing by a million (number of micromoles in a mole). For a given day, the total in each hour is added together to give us DLI. The light added to a greenhouse from supplemental lighting is added to the DLI calculations, and therefore influences growth and development.

Temperature

Virtual Grower uses average daily temperature to determine aspects of plant growth rather than by instantaneous temperature, day-time temperature, or night time temperature alone. The average daily temperature is calculated by using a weighted average of programmed temperatures (for your programmed heating schedule) and time, in hours, at each temperature.

Calculating Development (Time to flowering)

Each flowering species uses the same general model to predict time to flowering:

$$1/\text{days to flowering} = y_0 + T_1 \cdot \text{temp}_{\text{avg}} + T_2 \cdot \text{temp}_{\text{avg}}^2 + Q_1 \cdot \text{DLI} + Q_2 \cdot \text{DLI}^2 + TQ \cdot \text{DLI} \cdot \text{temp}_{\text{avg}}$$

Where y_0 is the reciprocal of days to flowering when temperature and light are zero, $temp_{avg}$ is the average daily temperature, T_1 is the linear parameter for the effect of $temp_{avg}$ on development, T_2 is the curvilinear parameter for the effect of $temp_{avg}$ on development, Q_1 is the linear parameter for the effect of DLI on development, Q_2 is the curvilinear parameter for the effect of DLI on development, and TQ is the parameter that allows any interactions between DLI and $temp_{avg}$.

Virtual Grower uses unique, empirically derived parameters to fit the above equation to predict development for each of the seven modeled floricultural crops. The structure of the equation above allows for temperature and light to act directly, in non-linear ways, and permits interactions between light and temperature. In most cases, one or more of the parameters are zero. Upon calculating the days to flower, Virtual Grower rounds the number of days to the nearest half-week. The references for the equations used for each species are:

- Adams, S.R., S. Pearson, and P. Hadlet. 1997. The effects of temperature, photoperiod, and light integral on the time to flowering of pansy cv. Universal Violet (*Viola x wittrockiana* Gams). *Annals of Botany*. 80:107-112
- Armitage, A.M., N.G. Seager, I.J. Warrington, D.H. Greer, and J. Reyngoud. 1990. Response of *Oxypetalum caeruleum* to irradiance, temperature, and photoperiod. *J. Amer. Soc. Hort. Sci.*
- Blanchard, M. and E. Runkle. 2008 (on-going). Temperature and daily light integral effects on crop timing and quality of bedding plants. PhD dissertation, Michigan State University.
- Erwin, J, R. Heins, R. Berghage, and B. Kovada., 1990. Temperature effects *Schlumbergera truncata* "madisto" flower initiation. *Acta Hort.* 272:97-101.
- Faust, J.E. and R.D. Heins. 1994. Modeling inflorescence development of the African violet (*Saintpaulia ionantha* Wendl.). *J. Amer. Soc. Hort. Sci.* 119:727-734.
- Frantz, J. M., Ritchie, G., Cometti, N. N., Robinson, J., and Bugbee, B. 2004. Exploring the limits of crop productivity: Beyond the limits of tipburn in lettuce. *J. Amer. Soc. Hort. Sci.* 129:331-338.
- Karlsson, M.G., R.D. Heins, J.E. Erwin, and R.D. Berghage. 1989. Development rate during four phases of chrysanthemum growth as determined by preceding and prevailing temperatures. *J. Amer. Soc. Hort. Sci.* 114:234-240.
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We are currently working to add more species to future versions of Virtual Grower.

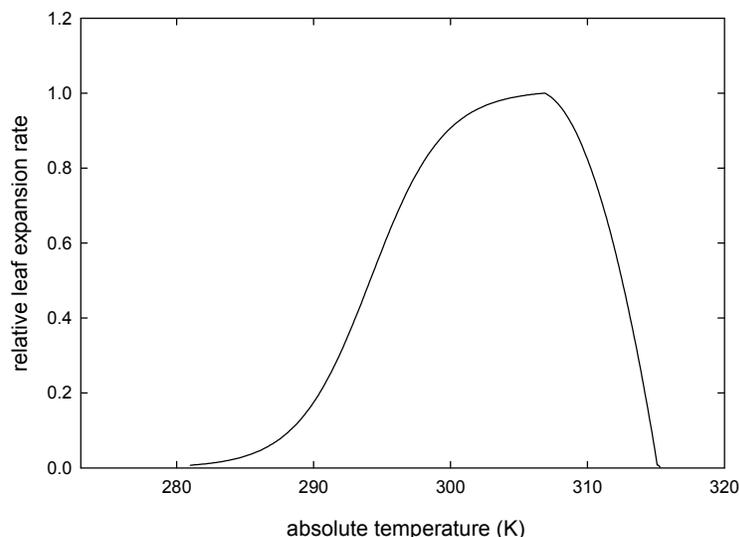
In a typical greenhouse environment, DLI changes daily, but the empirically derived equations are based on laboratory-maintained, constant DLI. Virtual Grower uses the average monthly DLI at the simulated location instead of variable DLI.

Calculating Growth

Leaf expansion

Before a plant can photosynthesize and make use of the available light, that light must be intercepted by a leaf. Therefore, leaf expansion must be considered. The general rate of leaf expansion is assumed to be independent of the species for the sake of simplicity for this model. It is sensitive to average daily temperature, however, and the optimum temperature for this leaf expansion is species dependant, based on a lower-limit to temperature, where possible. If no lower limit for temperature is reported, grower feedback was used to guide us into an approximation for the lower temperature limit for the difference species. The temperature optima (T_{opt}) are then 50°F warmer than that base temperature. Leaf expansion stops at hot temperatures, and that is modeled to be 12°F above the temperature optimum. Each species has a defined T_{opt} and is based on a reported lower-limit for plant growth for that species, where possible. If none is reported, grower feedback was used to guide us into an approximation for the lower temperature limit for the difference species.

The leaf expansion rate has two equations. One equation is used for the temperature from the lower-limit to the temperature optimum and the other is from the temperature optimum to the upper, critical temperature at which expansion stops. Together, these curves yield the following temperature response curve:



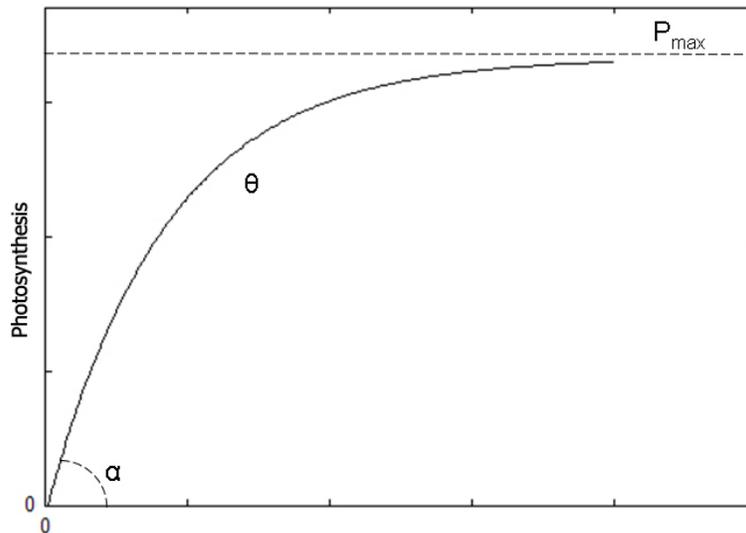
The actual temperature optimum (temperature that gives the largest relative leaf expansion rate) depends on the species.

Photosynthesis

Many excellent models have been published that accurately predict photosynthesis at the single leaf, whole plant, or whole canopy level. Some of these models have been further modified to account for species differences, water availability, humidity, CO₂ concentration, light, nutrition, and photosynthetic pathway, to name a few.

The goal of this component of Virtual Grower was to give a user feedback on how large a plant might be given their management conditions. The actual plant size will vary based on many of the environmental conditions listed above (nutrition, water availability, etc.) as well as starting size of the plant material and pot size. Use the plant size output as feedback on how large or small relative to other environmental settings *within other Virtual Grower simulations* to see the impact on overall plant performance.

The model that is used is based on a commonly used, single-leaf layer model. Selected primarily for its simplicity, the model allows for CO₂ temperature, and light responses, all of which are manipulated in greenhouse production, whereas fertility and water availability are often assumed to be optimal, and the photosynthetic pathway for the vast majority of greenhouse crops is the C3 pathway. Photosynthetic responses to light often look like this:



The initial steepness of the curve (α) depends on things like CO₂ concentration (among other things), the “elbow” of the curve (θ) depends on leaf angle, and the upper limit of the curve (P_{max}) depends on things like light, temperature and CO₂. For a more complete discussion of modeling photosynthesis, we have found the references at the end of this appendix to be useful.

The model’s equation is:

$$\text{Photosynthetic rate} = \frac{1}{2} \cdot \theta \left\{ \alpha \cdot \text{light}_{\text{instant}} + P_{\text{max}} - \left[(\alpha \cdot \text{light}_{\text{instant}} + P_{\text{max}})^2 - 4 \cdot \theta \cdot \alpha \cdot \text{light}_{\text{instant}} \cdot P_{\text{max}} \right]^{1/2} \right\}$$

Where α is the quantum yield (or photosynthetic efficiency), $light_{instant}$ is the instantaneous light inside the greenhouse at that time, and P_{max} is the maximum rate of photosynthesis theoretically possible.

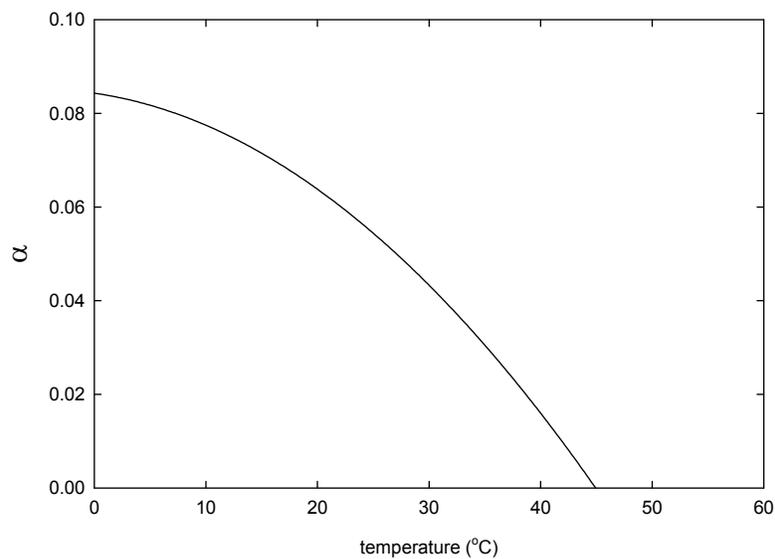
We have made a few simplifying assumptions. θ is defined as 0.8, which is often used for generic plants, P_{max} is set to 100, and α is maximum at 0.084 mol C fixed per mol photons absorbed (this value is open to some controversy, but we have assumed a fairly conservative maximum efficiency for this model; see references for a discussion on this value).

α and P_{max} both respond to temperature and CO_2 . These are modeled using the following equations:

α and temperature

$$\alpha = 0.0843 - (0.0003 \cdot \text{current temperature}) - (0.0000341 \cdot \text{current temperature}^2)$$

To yield the following response curve to temperature:



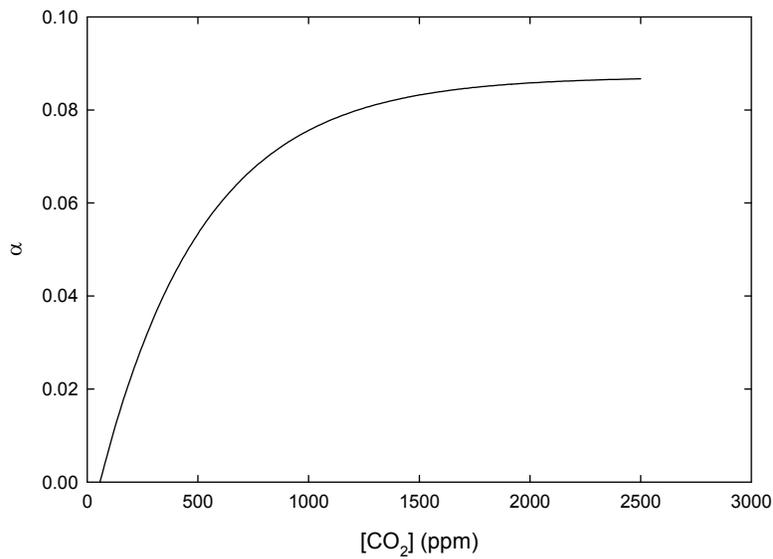
This response is based on Long, (1991), adjusted lower so that maximum α is 0.0843 mol C fixed per mol photons absorbed.

α and CO_2

α responds strongly to the concentration of CO_2 in the air. Current atmospheric CO_2 concentrations are approximately 400 ppm, but optimum photosynthesis for most greenhouse-grown crops occurs at a CO_2 concentration of 1000 to 1200 ppm. Very high CO_2 concentrations (~10,000 ppm) inhibit photosynthesis, but these concentrations are rarely encountered within a greenhouse. The equation Virtual Grower uses to describe the improved efficiency of α is:

$$\alpha = -0.0116 + 0.987 \cdot (1 - e^{(-0.0021 \cdot [CO_2])})$$

To yield the following response curve for CO_2 :

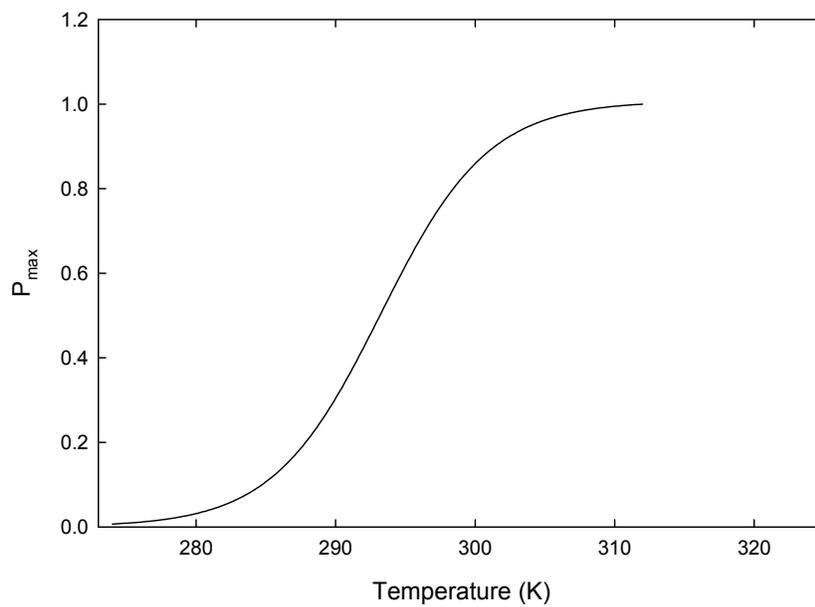


P_{max} and temperature

The maximum rate of photosynthesis depends on temperature and CO₂ and is adjusted, up and down relative to its max value (for this model) of 100 by the following equations:

$$P_{\max} = 51.42 / \{1 + e^{[-\text{absolute temperature} - (T_{\text{base}}+17)]/4.92}\}$$

To yield the following response curve for temperature:



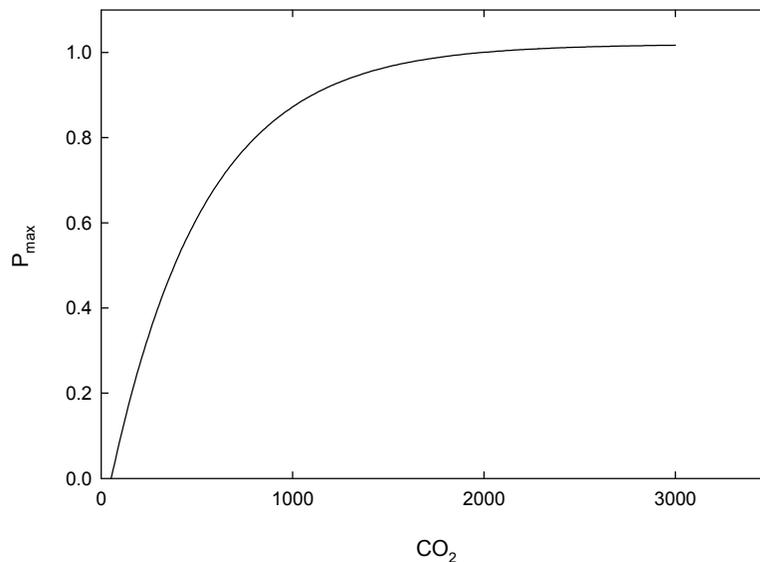
Note that in this equation, P_{max} does not decline in super-optimal temperatures. Sensitivity analysis of this simplifying assumption revealed little changes in overall growth due to the decline of alpha at elevated temperatures as well as decreased leaf expansion at these temperatures.

P_{max} and CO_2

The following equation is used to predict how P_{max} is influenced by CO_2 :

$$P_{max} = -0.116 + 1.136 * (1 - e^{-0.002 * [CO_2]})$$

To yield the following response curve for CO_2



The final plant size is calculated from a running total of predicted photosynthetic rates for the predicted leaf area exposed to the light environment for every hour during the scheduled interval.

Useful References for Modeling Photosynthesis

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Appendix 8: Estimating heating system efficiency

As stated in the general manual, the estimate for heating system efficiency uses general descriptions of a few key features of most heating systems to “dial in” an overall heating system efficiency. The heating efficiency section is based on a matrix of measured and reported values of similar system parts that engineering colleagues have measured or documented in “the field”. Virtual Grower uses four components, each with an efficiency of 0 to 100%, in theory. In practice, some of the components have a much more limited range (for example, maintenance ranges from 90 to 100%). As the user selects system components and descriptions that are similar to their system, the individual efficiencies are multiplied together to produce an overall system efficiency.

For example, selecting a Unit heater starts the efficiency matrix at a number, say 85% (a value that is often reported on the sides of heaters or in their manuals and can therefore be entered directly by the user as an override value). Power-vented units are more efficient than typical gravity ventilation, so that component may have a 90% efficiency by itself. Note that these two incorporate to some degree combustion efficiencies. Selecting a heat delivery option of overbench heating with no tube might have an individual efficiency of 60%. Finally, maintenance and age need to be considered, and if the heater is fairly new (3 to 5 years) and has been taken care of reasonably well, “maintenance efficiency” may have about a 95% efficiency. In this example, the system efficiency is 43.6% ($85\% \times 90\% \times 60\% \times 95\%$).

When we originally developed the matrix, we calibrated it to measured efficiencies at a number of greenhouses using many of the listed heating systems. We found “real” life cycle system efficiencies for many of the unit heaters was only around 50%. One of the goals of this matrix is to allow a user to see the impact that each choice makes on the overall system efficiency.

Note that this matrix should be treated as a ballpark estimate only and should not substitute for a licensed engineer to thoroughly evaluate your system. Realizing that we truly do not know some of these numbers, we do 2 things: 1) we allow for a user override and 2) we limit the efficiencies on ventilation and maintenance efficiencies to between 90 and 100% so they do not penalize the overall system too much.

Appendix 9: Calculating lighting costs

The costs per day that are calculated for a greenhouse utilizing supplemental lighting are based on number of lamps, wattage of those lamps, the wattage of the ballasts, hours per day the light is used, and electricity costs in the following manner:

of lamps * (lamp + ballast wattage) * hours * electricity costs

Remember to convert the lamp wattage to kW since electricity costs are likely in kW-h. For example, in a greenhouse containing 20 400-W lamps running off of 64-W ballasts for 6 hours at an electricity cost of \$0.13 per kW-h, the cost per day would be:

$20 \text{ lamps} * [(400 \text{ W} + 64 \text{ W})/1000] * 6\text{-h} * \$0.13 \text{ kW-h} = \$7.24$

This calculation is based on the example provided in:

Fisher, P. and A.J. Both. 2004. Supplemental lighting technology and costs.

From *Lighting Up Profits*, Edited by P. Fisher and E. Runkle. Meister Media Worldwide, Willoughby, OH.

In *Virtual Grower*, each of these parameters can be set, and the hours the lamps are activated can be variable depending on the weather and threshold settings.

The type of lamp selected is important when lighting units are changed, and in the use of light provided at plant level to calculate DLI in the plant growth and development sections. The conversions the *Virtual Grower* uses are summarized in the table below:

Unit	High Pressure Sodium	Metal Halide	Cool White Fluorescent	Incandescent
footcandles	1	1	1	1
lux	10.76	10.76	10.76	10.76
$\mu\text{mol m}^{-2} \text{ s}^{-1}$	0.13	0.15	0.15	0.22
W m^{-2}	0.026	0.033	0.032	0.043

This table is adapted from the version presented in:

Fisher, P. and E. Runkle. 2004. Managing lighting in the greenhouse – why is it important? From *Lighting Up Profits*, Edited by P. Fisher and E. Runkle.

Meister Media Worldwide, Willoughby, OH.